SYNOPSIS

for

PRE – SUBMISSION SEMINAR

of

Ph.D. Research in Geography

10.12.2021

Soumendu Chatterjee
Professor & Head
Department of Geography
Presidency University
86/1, College Street, Kol.-73

on

Geomorphic and Ecological Assessment of Lower Silai Corridor for Stream Restoration

submitted by

Sayoni Mondal

Registration No.: R-16RS12220077

Date of Registration: 14th March, 2017

Department of Geography

Faculty of Natural and Mathematical Sciences

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Geomorphic and Ecological Assessment of Lower Silai Corridor for Stream Restoration

Introduction

Fragmentation of fluvial ecosystems due to increased human encroachments into riparian environments has induced alterations in natural stream functions. Besides the direct hydro-morphologic adjustments brought about by in-stream structures like dams (Schmutz & Moog, 2018), river channelization (Kennedy & Turner, 2011), concretised and reveted bank slopes and embankments (Wu et al., 2017), and incessant mining activities (Asraf et al., 2011), much of the naturally vegetated corridors have been replaced by intensively cultivated lands to support growing populations. This has caused habitat fragmentation, loss of habitat diversity and most importantly, disruption of the channel-floodplain linkage, resulting in impaired stream health (Gurnell & Grabowski, 2016). The above necessitates river health appraisal from an integrated eco-hydrogeomorphic perspective that can effectively pinpoint impaired river stretches and their major stressors.

For such impaired river stretches, the failure of structural mitigation measures in providing long-term channel stability and restoration has prompted the use of active/non-structural rehabilitation measures. These seek to enable the river to attain an almost pristine condition that had existed prior to its degradation or take on a new, more stabilised form (Mondal & Patel, 2018). With increasing use of hydrogeomorphological concepts for integrated stream assessment and restoration, the focus has now shifted to eco-engineering techniques that centre around reach-scale evaluations instead of considering larger spatial units and aim to link the channel morphology with its hydrological and ecological aspects. Vegetation-based bio-engineering techniques are thus the need of the hour which not only help the channel attain its stability but also regenerate riparian ecosystems and restore channel-floodplain linkages. These have been proven to be long-term measures that can feasibly take the degraded river back to its near-pristine state, thereby promoting stream stabilisation and habitat diversification (Mondal & Patel, 2020).

Therefore, this doctoral thesis tries to highlight the effectiveness of using ecologically efficient live vegetation techniques as a suitable channel corridor management strategy in mitigating common fluvial hazards along the Silabati River in West Bengal. The existent environmental stressors herein presently degrade the channel and riparian ecosystem and cause overall impairment of the stream health and floodplain corridor. A reach-level channel health examination is thus undertaken, combining different indices, so that targeted restoration sites can be prioritised and the probable causes of their degradation be identified.

Study area

The Silai River (also known as River Silabati) (Fig. 1), is a major right bank tributary of River Rupnarayan. It is 221 km long, having a catchment area of 4150.9 km^2 and drains 22 blocks and 3412 mouzas across Puruliya, Bankura and Paschim Medinipur districts of West Bengal. It has a number of tributaries that contribute significantly to the overall discharge, often causing sustained floods and bank instability in its lower course.

Geologically the Silabati Basin is diverse, comprising of residual Archaean granites that underlie the undulating pediplain surfaces in the headwater reaches. This terrain grades into the deeply weathered duricrust zone that corresponds to the Lalgarh Formation, which covers extensive parts of the basin in its south western portion. The lower floodplains towards the east and south east are covered by Quaternary alluvium. Being a plateau-fringe basin, the river has a moderate degree of confinement in its upper reaches and shows traces of incision whereas the low confinement level in its middle and lower courses leads to the presence of wide floodplains and free lateral migration across the alluvial tract.

The basin experiences a wet and dry tropical climate with an average annual rainfall of 125 - 143 cm, which is mainly concentrated during the south-west monsoon months of July to September. Substantial stretches of the river either dry out or have low water level during the lean season. Precipitation gradually decreases from the basin mouth towards the headwater stretches and thus a distinctive vegetation gradation can also be noticed along this transect. The characteristic vegetation of the region is of dry deciduous type, with some xerophytic scrubs and bushes that have adapted to the harsh climatic regime, especially in the northern and western region, which has unreliable and erratic precipitation and nutrient depleted soils.

The land use in the region also corresponds to this vegetation gradient. The wetter tracts of the basin (almost 61% of the area) are used for intensive cultivation (mono/double-cropped), especially along the middle and lower reaches by clearing the riparian forests. This allows only a small portion of the original vegetation (20%) to be retained in the basin, with it mostly concentrated in scattered pockets in the headwater zones and on the lateritic uplands in the south western part. Plantations and orchards comprise 0.9% of the basin area.

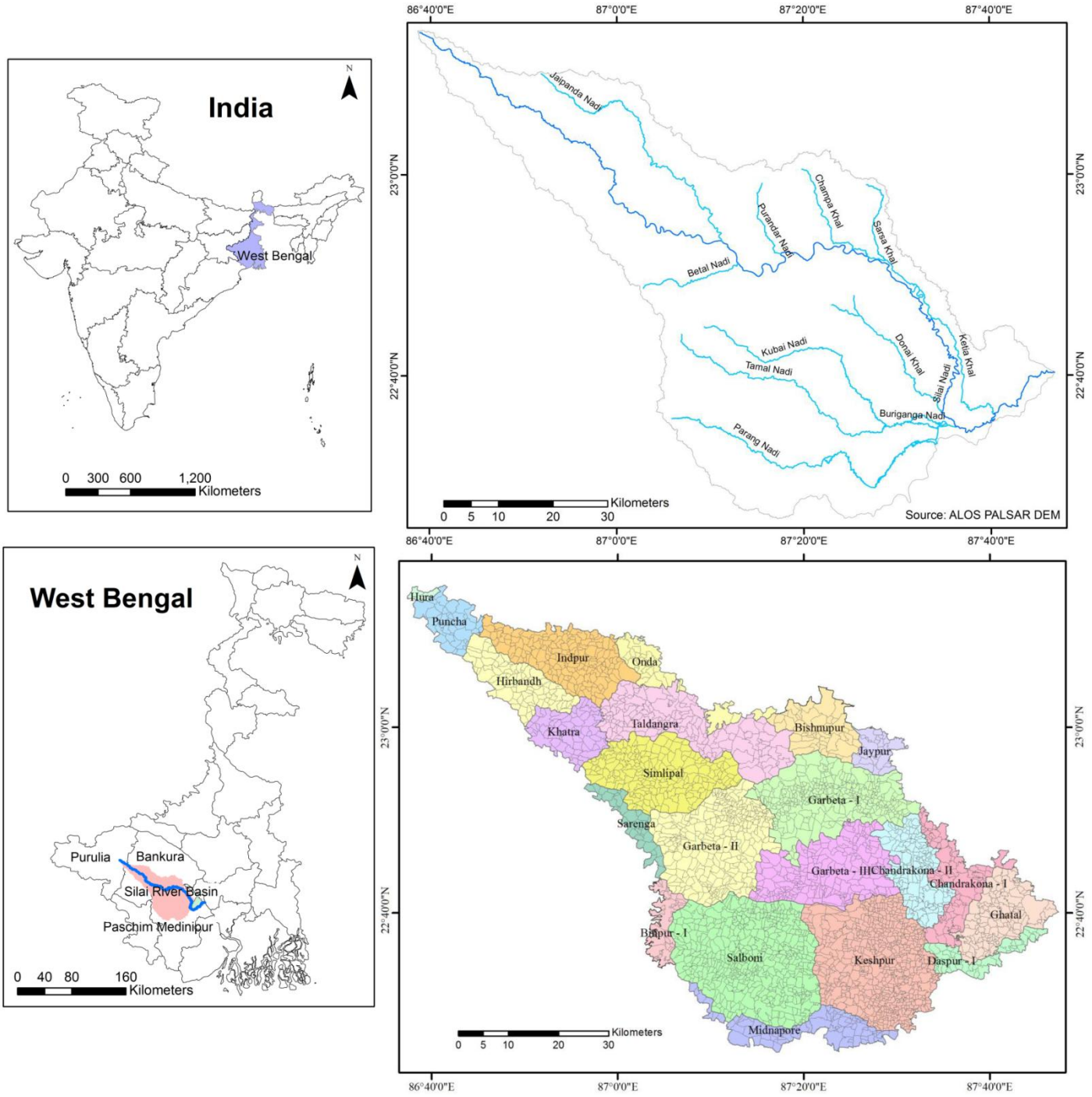


Fig. 1: Location of the Silai River Basin, with main channel, tributaries and administrative units

Major objectives

Based on the above discussion, the major objectives of the present research are as follows:

- to demarcate channel reaches of similar geomorphic character using a stream classification system
- to examine the geomorphic, hydraulic and ecological conditions of the channel within the delineated reaches and analyse the nature of fluvial hazards within the impaired reaches
- to formulate suitable management practices through riparian corridor management and river restoration methods for flood hazard and streambank instability mitigation

Datasets and methods

All necessary information regarding basin attributes like lithology, geomorphology, physiographic divisions, soil, climate, geohydrological condition, and the present land-use/land cover status was obtained from various institutes, online data repositories, libraries and government departments. The planimetric map database was prepared from the Survey of India Topographical Sheets 73I/12, 73I/16, 73J/13, 73M/4, 73M/8, and from the ALOS PALSAR Digital Elevation Model (DEM) having 12.5 m resolution. Use of medium to high resolution satellite images of Landsat 5/7/8 (30 m) and Resourcesat 2A LISS-IV MX (5.8m) scenes along with the Google Earth platform further aided the reach-level assessment of stream health. Water level data was obtained from the Irrigation and Waterways Department, Government of West Bengal's web portal while channel geometric data was generated from in-depth field surveys using sophisticated hydrological survey equipments like echosounder, current meter, total station and dumpy level. The tested soil and grass root samples were collected from field surveys.

The detailed step-wise description of the followed methods is stated below along with a schematic diagram of the same (Fig. 2):

- Demarcation of broad channel stretches based on basin physical attributes like geomorphology, lithology, soil and land-use practices and its further subdivision into almost homogenous segments of 2 km each. Use of the Rosgen Natural Channel Classification System to characterise these reaches for channel health assessment.
- Detailed assessment of stream health using multi-parametric integrated eco-geomorphic indices, namely, Morphological Quality Index (MQI), Qualitat del Bosc de Ribera Index (QBR), Riparian Strip Quality Index (RSQI), Normalised Difference Vegetation Index (NDVI) and Water Quality Index (WQI). Prioritisation of sites in need of immediate restoration along with identifying the major stressors in the concerned reaches was done using the devised score-based reach quality rating scheme.
- Identification of the major factors which cause river health impairment in these reaches (principally sand-mining) along with ascertaining the stretches prone to channel instability, annual flooding and bank erosion. The nature of these hazards herein and their effects was assessed in detail.
- The spatio-temporal extent and distribution of sand mining activities was examined and the morphological and ecological alterations caused as a result were quantified. Assessment of annual bank erosion rates and sediment loss was done using the dynamic Bank Assessment of Nonpoint Source Consequences of Sediments (BANCS) model. The Universal Soil Loss Equation (USLE) was used to highlight zones of maximum annual soil loss and to prioritise

sub-basin catchments where eco-engineering strategies could be implemented to arrest excessive soil loss and land degradation.

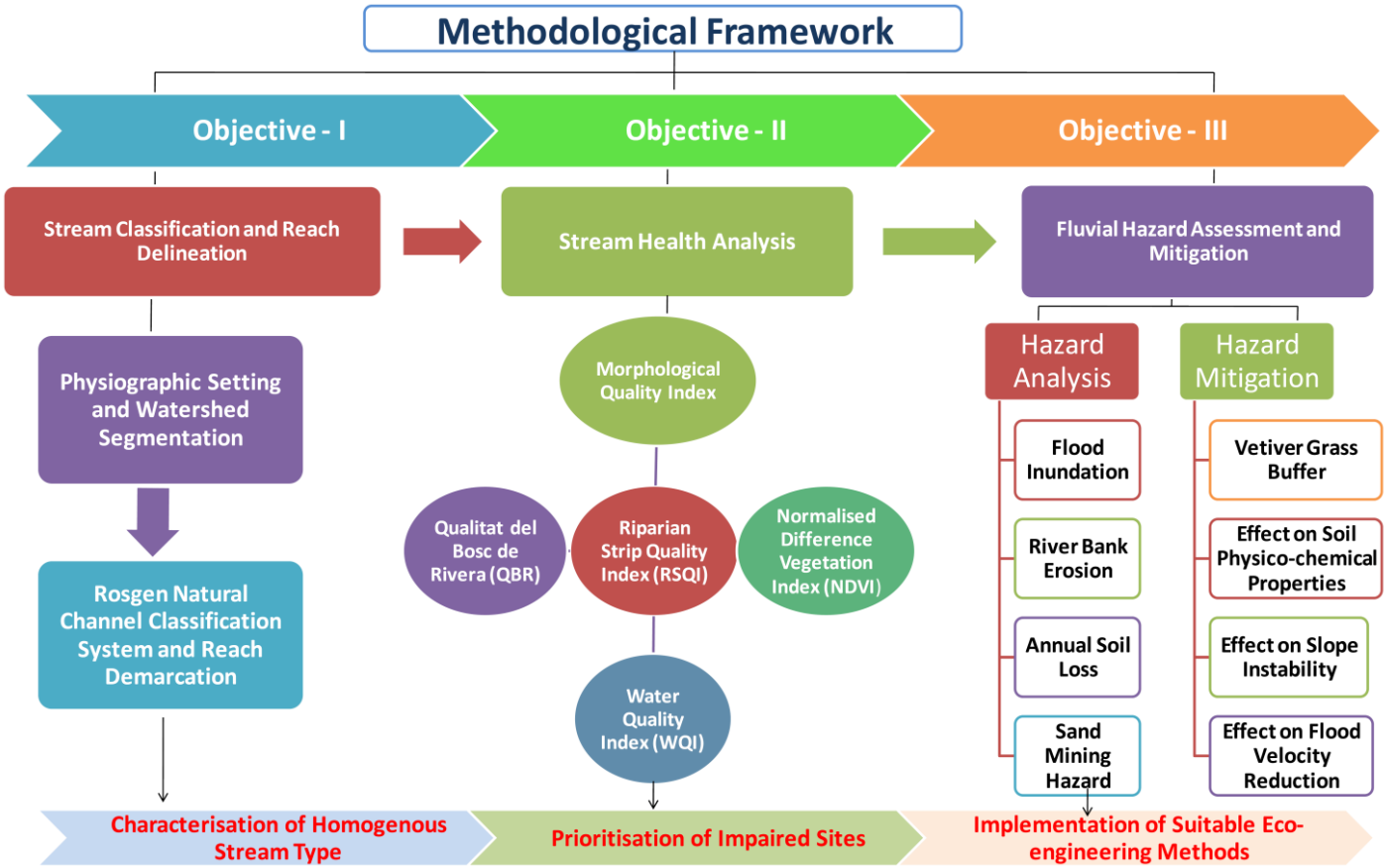


Fig. 2: Flowchart of the workflow in the thesis

- Flood inundation assessment in the region has been done using the European Commission Joint Research Centre's Global Surface Water dataset (Pekel et al., 2016) to identify zones of annual inundation, their seasonality and recurrence that would help to locate river stretches where implementation of bioengineering techniques can bring about best results.
- Lastly, the effectiveness of ecological techniques using live vegetation buffers (Vetiver grass) in mitigating flooding and bank erosion hazards through reduced flood peaks and water velocities in the flood-affected regions was examined using a 1-D inundation model (HEC-RAS). The effect of grass root reinforcement on slope stability was examined along with its impact on the soil physico-chemical properties. A cost-benefit analysis of implementing this method and the related bottlenecks was ascertained in field test sites.

Chapterisation

The thesis has been structured in a systematic way, with the chapters being as follows:

Chapter-1 — Introduction

- Defining channel corridor/riparian buffer; importance of river corridor studies
- Defining river restoration; restoration types; its economic and ecological importance
- Global literature review on river restoration practices and examples
- Importance and necessity in India; brief review of studies in India
- Frameworks of riparian ecosystem assessment; Hydromorphological approaches
- Research gaps and reasons for choosing the particular study area
- Objectives; Datasets and methods
- Limitations of the study

Chapter-2 — Silai River Basin and its Channel Corridor: Basic attributes

- General description of the basic attributes: basin and corridor focus
- Stream course description
- Specific representation of geomorphic units within channel and corridor

Chapter-3 — Reach-level Riparian Health Assessment

- Riparian health assessment: a short introduction
- Channel classification schemes and details of the Rosgen Channel Classification System; Rosgen stream types in Silai River
- Stream ecogeomorphic indices- MQI, QBR, RSQI, WQI and NDVI: their description, enumeration and analysis
- Reach Prioritisation for restoration highlighting degraded/impaired sites

Chapter-4 — Riparian Hazards along a Lowland River

- Sand mining: mechanisms, affected reaches and channel changes
- Bank erosion occurrence and prediction: BANCS framework
- Basin-wide soil erosion: USLE estimates, affected areas
- Flood affected reaches: extent and duration

Chapter-5 — Eco-engineering methods for managing Fluvial Hazards

- Use of live vegetation in river restoration: brief review
- Vetiver grass characteristics and morphology; Vetiver use in soil-water conservation
- Using Vetiver buffer to check runoff and soil loss based on USLE zones
- Gholsai and Kuthighat village case studies on bank erosion mitigation
- Hydraulic modelling to check flood velocity using Vetiver buffer in HEC-RAS
- Cost comparison of hard and soft techniques
- Summary of successful examples of Vetiver plantation in Bengal showing other multipurpose benefits like water quality enhancement and rural income generation
- Implementation framework followed in Bengal with its pros and cons
- Analysis of overall viability of Vetiver grass buffers

Chapter-6 — Summary and Conclusion

Chapter-wise summary of the analyses done

Chapter-2 — Silai River Basin and its Channel Corridor: Basic attributes

The Silabati River and its principal tributaries have been delineated and described from the Survey of India Topographical sheets (No. 73 I/12, 73 I/13, 73 J/13, 73 N/1, 73 N/2, 73 N/5-7, 73 N/9, 73 N/10, 73 N/13, 73 N/14, 73 M/4, 73 M/8 and 73 M/12). Further detailed description of the channel course and sites along it were done based on information gathered through extensive field surveys and from Google Earth images.

Mapping and descriptions of the detailed basin physiographic divisions for the districts of Puruliya, Bankura and Paschim Medinipur (Fig.3a) were derived from the Geomorphological Map of India (GSI, 2002) for the respective districts and from the GSI repository (Bhukosh database). The surface lithology (Fig.3b) was mapped from the District Resource Maps that are based on the GSI Quadrangle Maps of Jamshedpur (73J), Puruliya (73I), Bardhhaman (73M) and Medinipur (73N) at a scale of 1: 250,000 and using the data layers obtained from the GSI's Bhukosh geoportal. Elevation data was derived from ALOS PALSAR radiometrically terrain corrected (RTC) 12.5m resolution DEM tiles obtained from the Alaska Satellite Facility Project of NASA (Fig. 3c) from which the slope map was derived (Fig. 3d).

Maps and descriptions of the basin soil cover and distribution and characteristics of the soil profiles (Fig.4a) were obtained from National Bureau of Soil Survey and Land Use Planning (NBSS & LUP) ICAR, Nagpur (scale = 1:50,000) maps and databases and from other soil data and reports collected from the respective district offices. The detailed land cover and land use map of the basin (Fig.4b) was prepared using the Biodiversity Information System (BIS) database of the Indian Institute of Remote Sensing (IIRS) at a scale of 1:50,000. The basin is almost entirely non-urbanised, with only a few built-up sites along its course.

The main Silai River channel corridor was demarcated and mapped following the Fixed-width Corridor Concept, wherein a 500 m wide buffer was created on either side of the channel to denote the riparian corridor that would highlight the stream morphology and ecology, specific human interferences and their consequent impacts on channel health. Few representative windows along the channel with its corridor were selected to ascertain the various geomorphic units that make the corridor an unique ecosystem and also to bring out the impact of human pressures on such geomorphic assemblages.

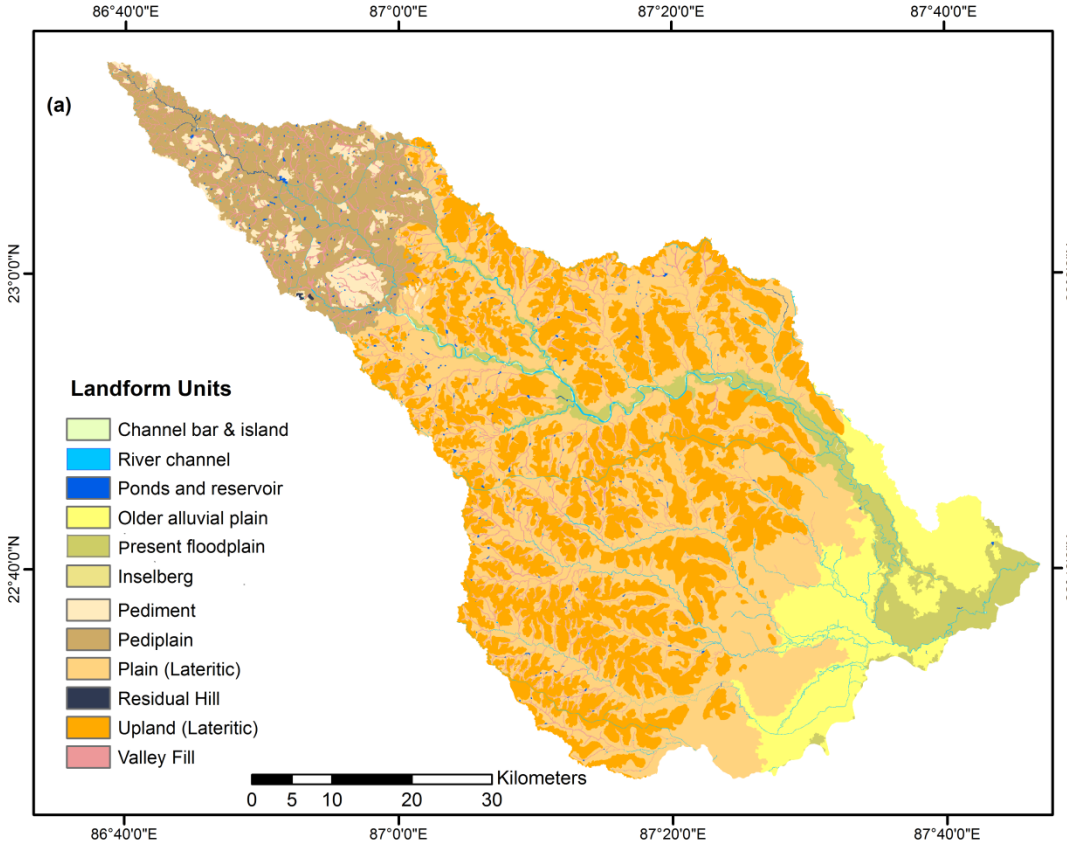


Fig. (3a): Broad physiographic units within Silai River Basin

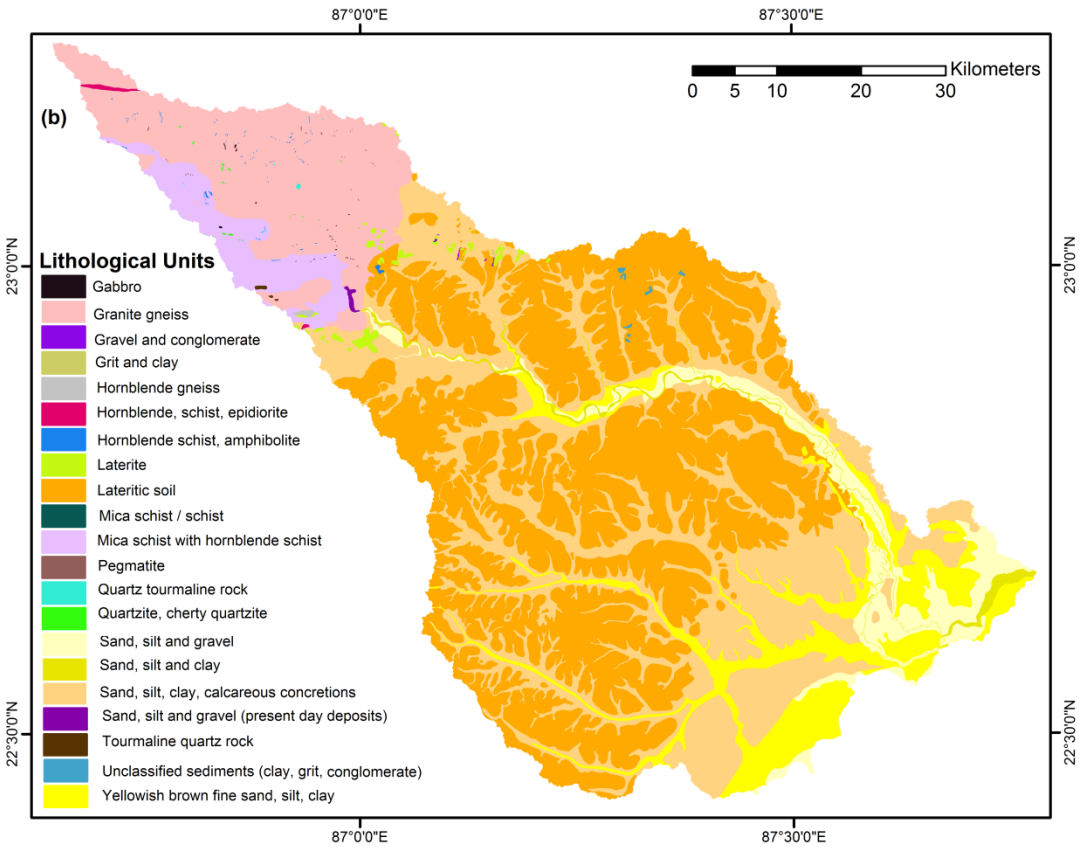


Fig. (3b): Surface lithology of Silai River Basin

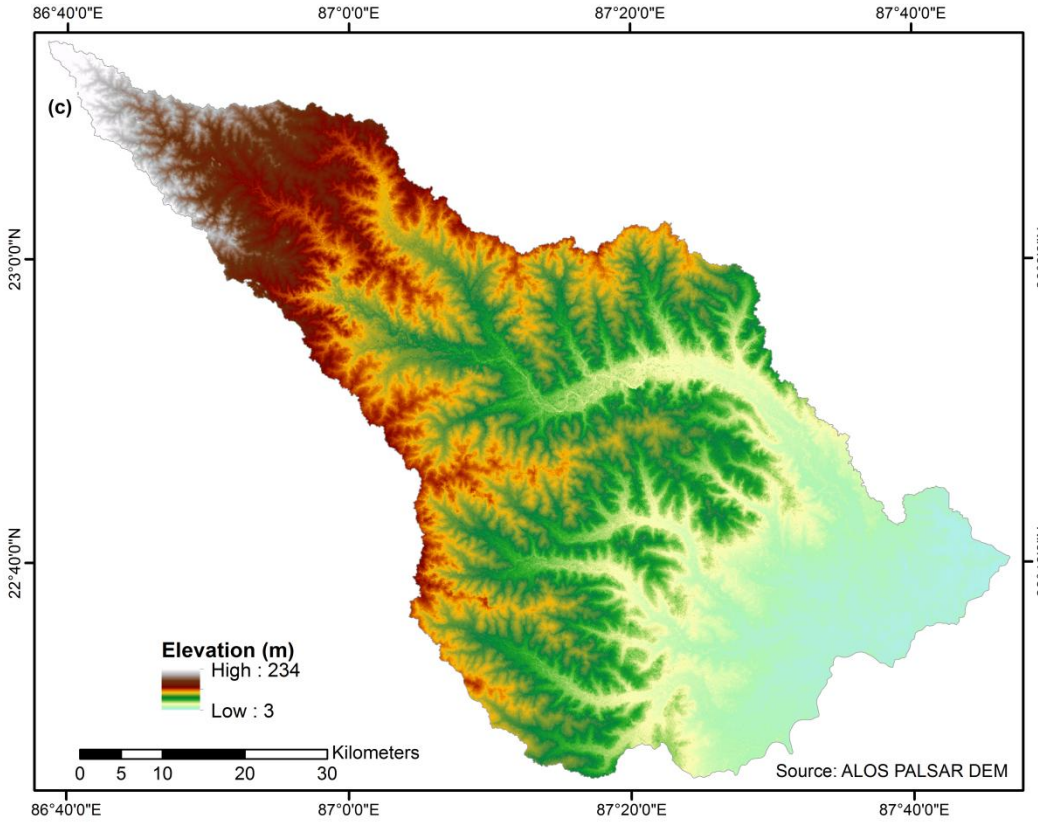


Fig. (3c): Elevation distribution within Silai River Basin

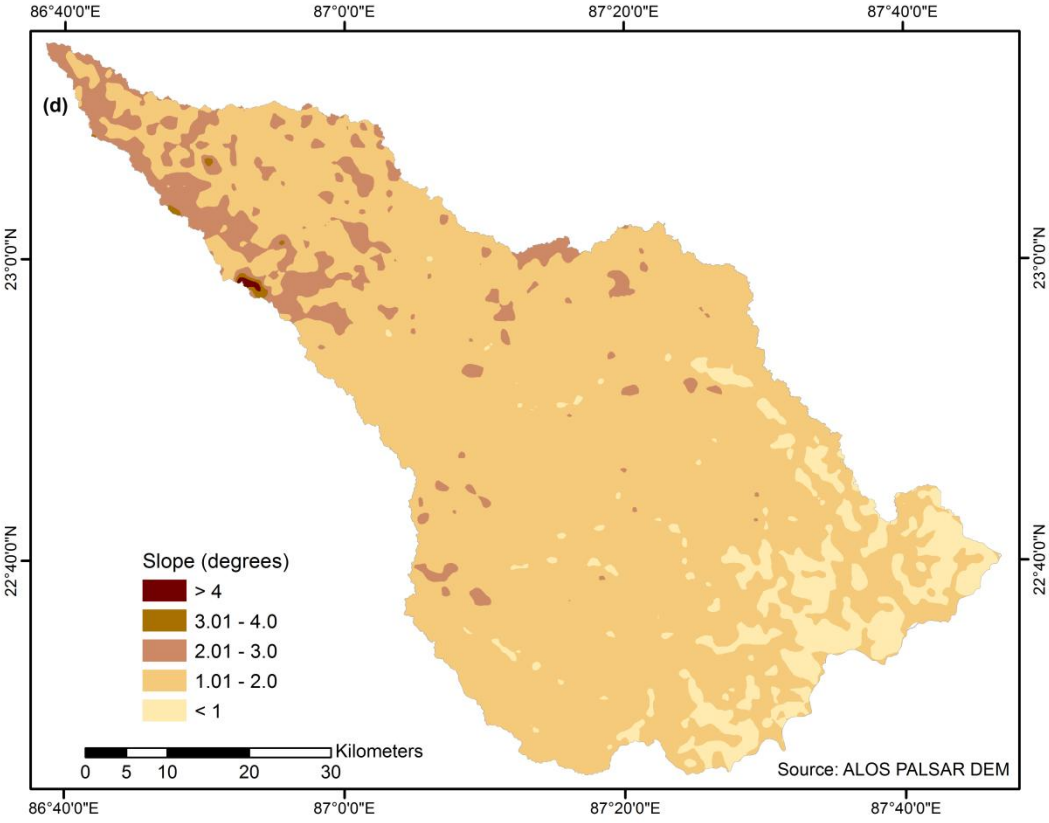


Fig. (3d): Slope map of Silai River Basin

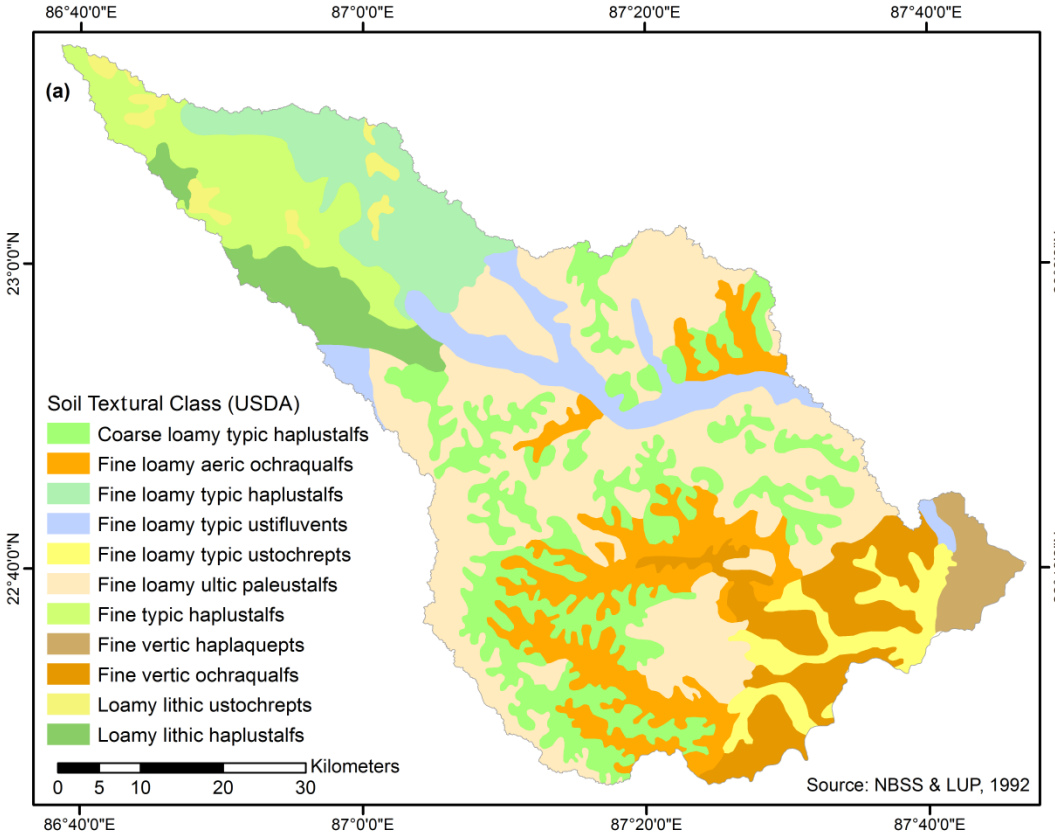


Fig. (4a): Distribution of soil textural classes (USDA) in Silai Basin

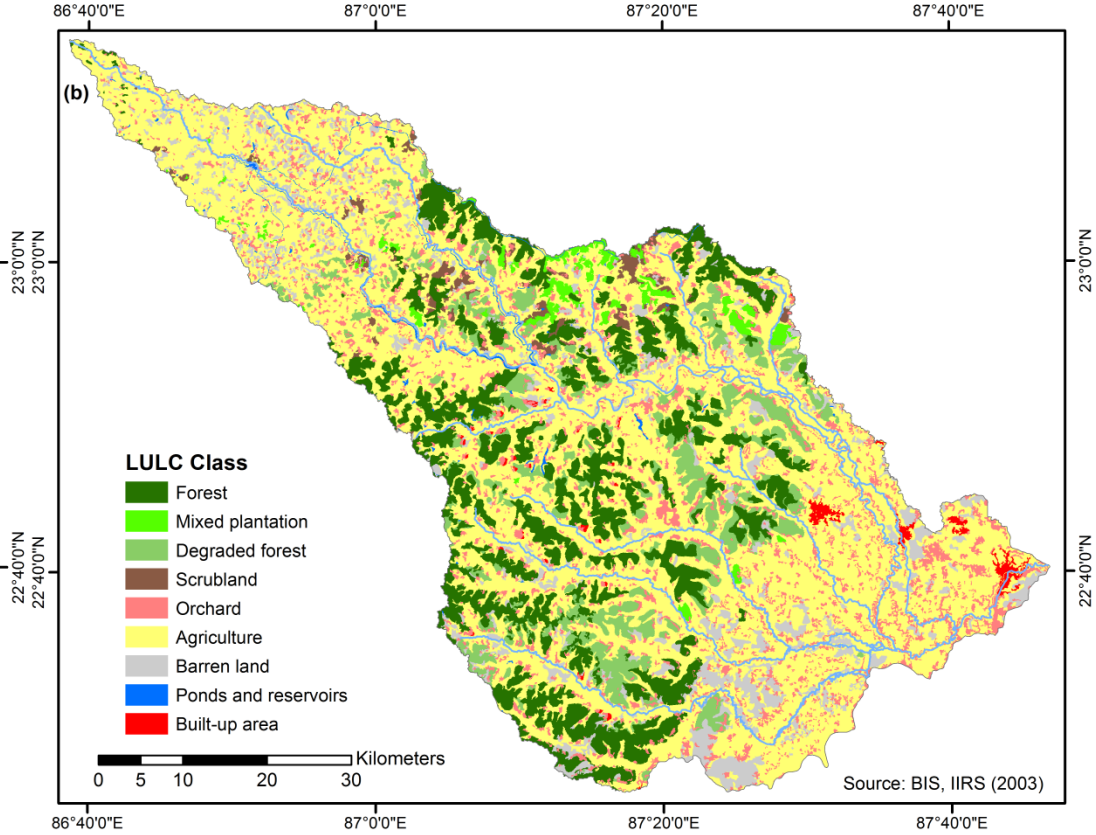


Fig. (4b): Land use and land cover map of Silai Basin

Chapter-3 — Reach-level Riparian Health Assessment

As a first step to river health appraisal, stream characterisation was done using the Rosgen Stream Classification system (Rosgen, 1994). The purpose of this classification was the identification of reaches that are homogenous in character, having specific hydraulic and sediment relationships, and are thus expected to behave similarly when a particular type of management strategy is applied to them. It is based on a four-tier assessment approach wherein the Level I classification allows a broad geomorphic characterization by providing the initial linkages between basin characteristics and valley types and landforms with the stream morphology. It identifies nine major stream categories designated as Aa, A, B, C, D, DA, E, F and G based on topographic and landforms maps and images, geologic and soil maps. Level II classification is based on more finely demarcated criteria to address questions of channel response to changes in flow and sediment regimes, natural stream recovery potentials and channel sensitivity to major disturbances. The delineative criteria involve factors like entrenchment ratio (ER), width/depth ratio (WDR), sinuosity, channel slope and the dominant channel material and these are primarily based on field measurements within the demarcated stream types. An illustration describes how each of the parameters were determined from the field as well as from Google Earth images (Fig.5) for each of the surveyed sites.

The entire length of the Silai River was classified accordingly into 117 reaches and three broad stream types (B, C and E), identified based on the Level I classification and further classified into 18 sub-categories (Fig. 6) that reflect their intrinsic morphologic and geometric properties according to the Level II classification.

Type B stream reaches are mainly found in the headwater zones, characterised by moderately steep to gently sloping terrains and having narrow valleys that limit the development of a wide floodplain. These are structurally controlled, moderately entrenched reaches having a moderate width/depth ratio of >12 and entrenchment ratios ranging between 1.4-2.2, with channel gradients of 2-4%. While the characteristic bed material is dominated by bedrock with an admixture of boulder, cobbles and sand, river banks contain finer particle sizes than the bed substrate and are often comprised of an unconsolidated mixture of finer gravels and sand. Sites like Chakla (S_012), Gandlugara (S_013), Salapahari (S_014), Junbedya (S_016) and Tilabani (S_033) are standout examples of this stream type.

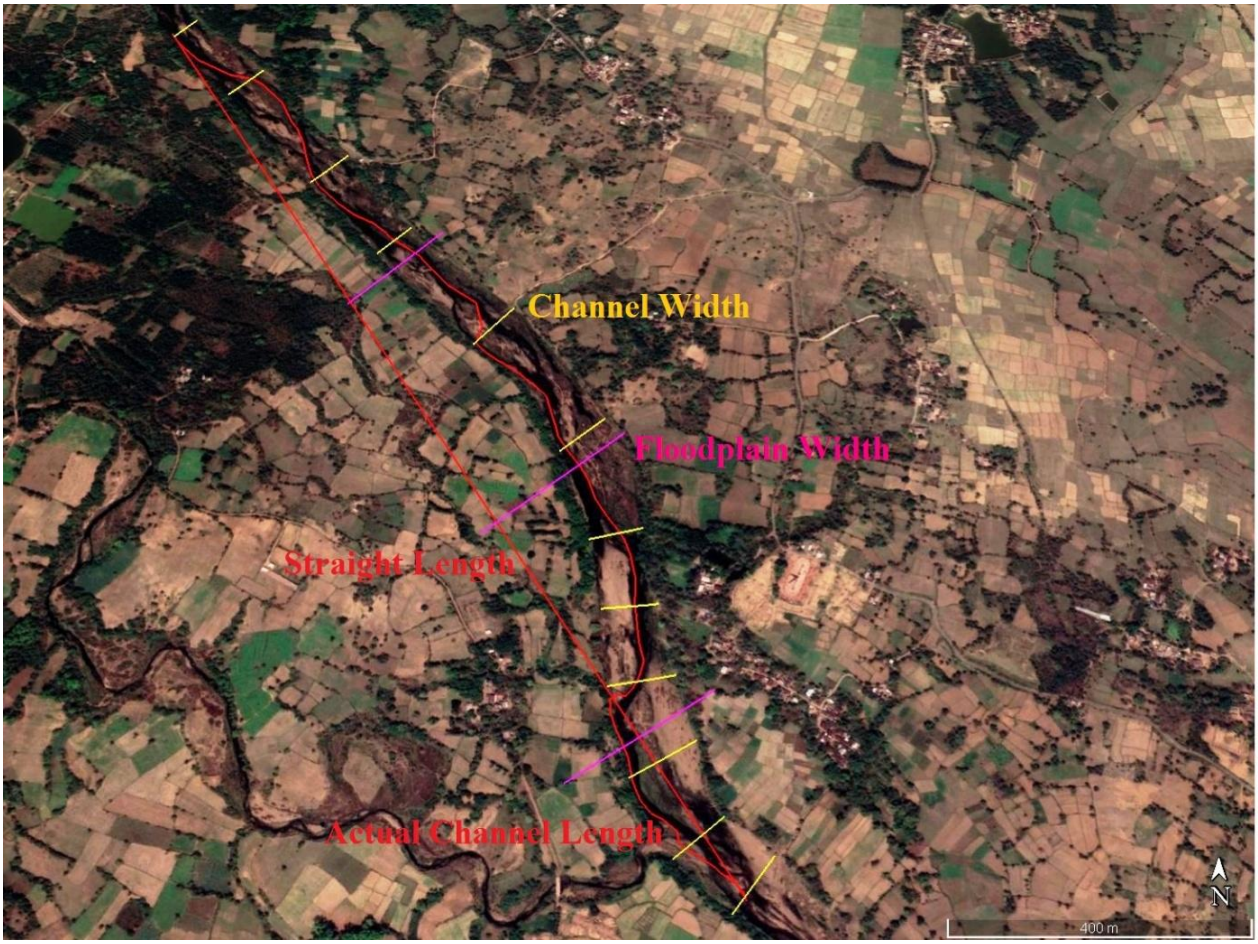


Fig. 5: Illustration of the delineative criteria for Rosgen Level II Stream Classification

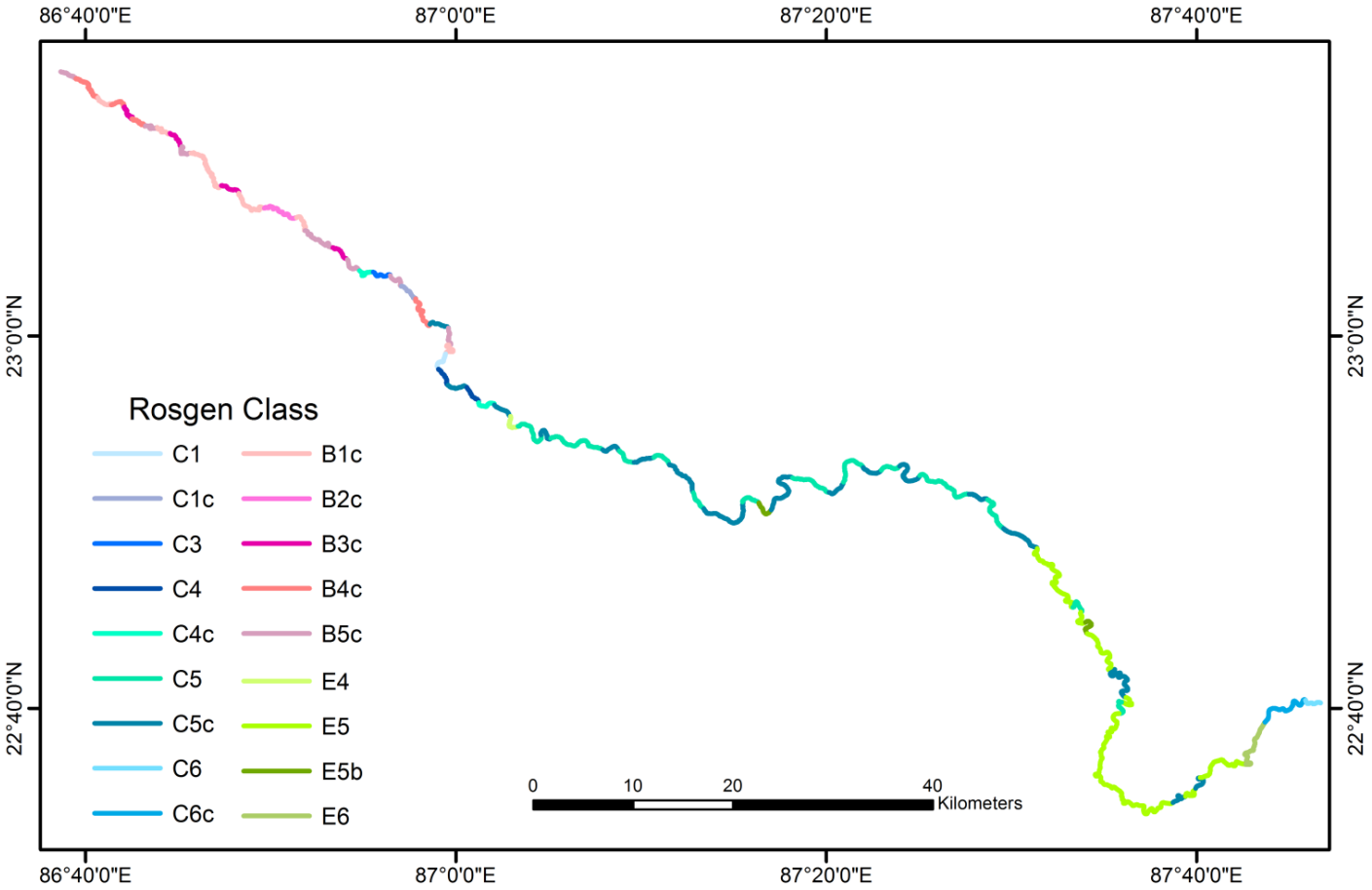


Fig. 6: Major Stream Types (main channel) according to the Rosgen Classification System

Type C stream reaches are characterised by meandering channels having low bedrock control and typically placed within narrow to wide valleys with well-developed floodplains. These channels exhibit high width/depth ratios as indicated by the channel cross-sectional shape and form and have average sinuosity of >1.2. Primary channel material for such streams changes from boulder dominated substrate to gradual predominance of gravel scours and sands. The dominant stream type along the majority of the middle course of the Silai is C5, characterised by meandering, sand-dominated, riffle-pool channels, having broad and well-developed floodplains that are typical of lowland rivers. Sites like Dogira (S_041), Simlipal (S_042), Mathurakata (S_047), Lakhiyapa (S_049), Patherberia (S_055), Nepura (S_059) and Rajballabhpur (S_074) all belong to this particular stream type.

The lower course exhibits E type streams that are slightly entrenched channels, characterised by low width/depth ratio and exhibit very high channel sinuosity, resulting in high meander-width ratio values and less than 2% channel slopes. Here, the channel exhibits an average sinuosity of >1.5 having channel depths of more than 5.5 m that carries water throughout the year. The high embankments, mostly along the right bank, have resulted in deeper, narrow channels, whose decreasing carrying capacity often results in annual floods occurring along these reaches. Sites like Banka (S_087), Nirbhaypur (S_092), Dingal (S_096), Nij Narajole (S_102), Bar Gobindo (S_108), Sitakundu (S_110) and Rashikganj (S_112) are typical examples of this stream type.

After successful delineation of the homogenous stream reaches, the existent stream health condition was determined within each of the 117 reaches using a number of eco-geomorphic indices following the hydrogeomorphologic principle of the European Union Water Framework Directive (WFD) which highlights the interlinkages between morphology, hydrology and ecology in defining stream geomorphic status. A representative site from each individual reach was taken as the unit of analysis. A flowchart shows the method used to discern the linkages that exist between the selected stream hydrogeomorphic indices (Fig. 7). The results of this were used to judge the deviation of the respective reaches from their relevant Reference Reach.

To gauge the morphological condition of the stream, Morphological Quality Index (MQI), devised by the Italian National Institute for Environmental Protection and Research (ISPRA) has been used (Rinaldi et al., 2012, 2013). The framework is designed into a structured hierarchy which evaluates stream geomorphic condition based on 3 main indicators- channel functionality, channel artificiality and channel adjustment which are further sub-divided into a set of 28 detailed horizontal and vertical sub-indicators of channel continuity, morphology and vegetation status, the individual scores of which are summed up to measure the degree of

alteration and the extent of naturalness of the basin. The index ranges between 0-1, with values close to 1 indicating a higher quality.

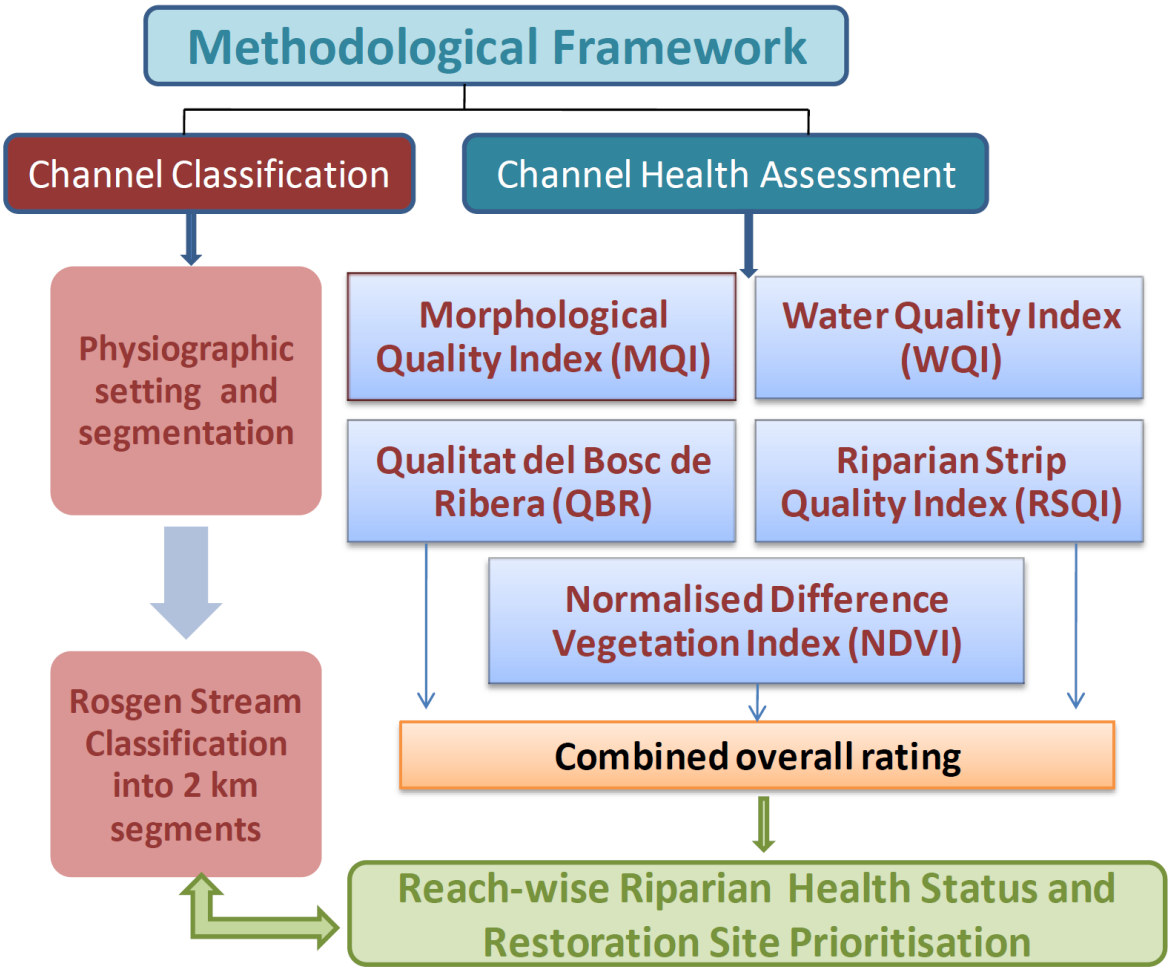

Methodological Framework
Channel Classification
Channel Health Assessment
Physiographic setting and segmentation
Morphological Quality Index (MQI)
Water Quality Index (WQI)
Qualitat del Bosc de Ribera (QBR)
Riparian Strip Quality Index (RSQI)
Normalised Difference Vegetation Index (NDVI)
Rosgen Stream Classification into 2 km segments
Combined overall rating
Reach-wise Riparian Health Status and Restoration Site Prioritisation

Fig. 7: Methodological flowchart of the workflow for Chapter 3

Intricately linked with the channel morphology is the reach-level water quality, with its deterioration likely to impact upon stream habitats. The Water Quality Index (WQI) was calculated using Horton's Method (1964) and CPCB Class D analysis taking the pH and DO parameters as the major indicators for the propagation of wildlife and fisheries (these being most related to natural stream health). Including the turbidity parameter gave further insight into the ambient reach water quality. A total of 351 water samples were collected along the entire river taking three samples (approximately 600 m apart) from each of the 117 reaches.

Not only does the stream condition depend upon the morphologic and hydrologic status, the much neglected ecological component, i.e. the riparian vegetation status and its continuity with the adjacent floodplain, assumes special importance in determining stream health. The Qualitat del Bosc de Ribera (Riparian Forest Quality) or QBR (Munne et al., 2003; Sirombra & Mesa, 2012) index was used to denote the quality of riparian vegetation using 4 indicators- total

riparian cover, cover structure, cover quality and the amount of anthropogenic alterations introduced into the channel. Each component was individually scored during field surveys by adding or subtracting the sub-components from a base score and the summation of all the four components gave the QBR value. This ranges between 0-100 and is categorised into five quality classes, in accordance with the WFD guidelines.

Further detailed insight into the amount of floodplain fragmentation and riparian vegetation transformation was obtained by using the 500 m buffer demarcated on either side of the channel. This was further subdivided into ten zones, 50 m width each, for a more detailed analysis of the strip-wise change in vegetation character as one moves away from the channel side. Land-use transformations and vegetation gradient within these zones were evaluated using the Riparian Strip Quality Index (RSQI), which provides a precise estimation of the same (Novoa et al., 2018). It is calculated on the basis of the relative area occupied by a particular land use within this strip, to which a weighted score is applied, that evaluates the potential of that particular class in fulfilling the ecological functions desirable to protect the riparian ecosystem. As such higher weights are assigned to pristine native vegetation or forest patches, whereas a comparatively lower score is given to land cover classes that are either built-up or have bare surfaces. Resouecesat-2A LISS IV MX images of January 2019 of 5.8 m resolution were processed to obtain the desired results. The vegetation condition obtained from the QBR and RSQI indices was validated using the Normalised Difference Vegetation Index (NDVI) which provides valuable information on vegetation form, its structure, vigour and density, productivity and biomass generation over large temporal scales, thus critically explaining the effects of vegetation removal on stream health (Pettorelli et al., 2011).

Lastly, combining the above indices, a final priority map was devised based on individual scoring of the indices that highlights the sites most affected by anthropogenic activities, which have impaired morphological functions and requiring immediate restoration to retain its usual geomorphic functionality. The overall quality was categorised into a five-point scale such that a rating of 1 was assigned to the best quality class of a certain index and a rating of 5 to the worst quality class. The individual scores for each of the indices were summed up to obtain the overall quality class that denotes the overall channel quality of the respective reaches. This was classed from A to E, where A represents a quality class which is least affected by human alteration and is thus most pristine, while a quality class E denotes the most impaired reach requiring highest priority of restoration. A second quality rating scale was devised taking the turbidity parameter and the number of sand mining sites within a reach into consideration to include the specific effects of these parameters into analysis. Both rating classes were standardised in order to arrive at a similar scale for both of them.

An overall MQI score of 0.68 was recorded for the entire Silai channel (Fig. 8), which has been classed as having moderate quality. However, while the upper and the lower segments record moderate to high MQI scores of 0.71 and 0.69, respectively, the middle stretch shows significantly lower quality (0.63) as compared to other reaches. With regards to the vertical sub-indices (Fig. 9), alteration of the overall channel functionality was 58.88%, followed by an artificiality of 20.37% and change in channel adjustments being 16.95%. A breakdown of the horizontal sub-indices (Fig. 10) highlighted a more detailed picture of characteristic alterations, with a mean morphological alteration of 30.77%, 27.26% alteration in channel continuity and 78.90% alteration in vegetation cover. The deviation of reach-wise morphological quality from the respective reference reaches was also calculated for the three major stream types (Fig. 11).

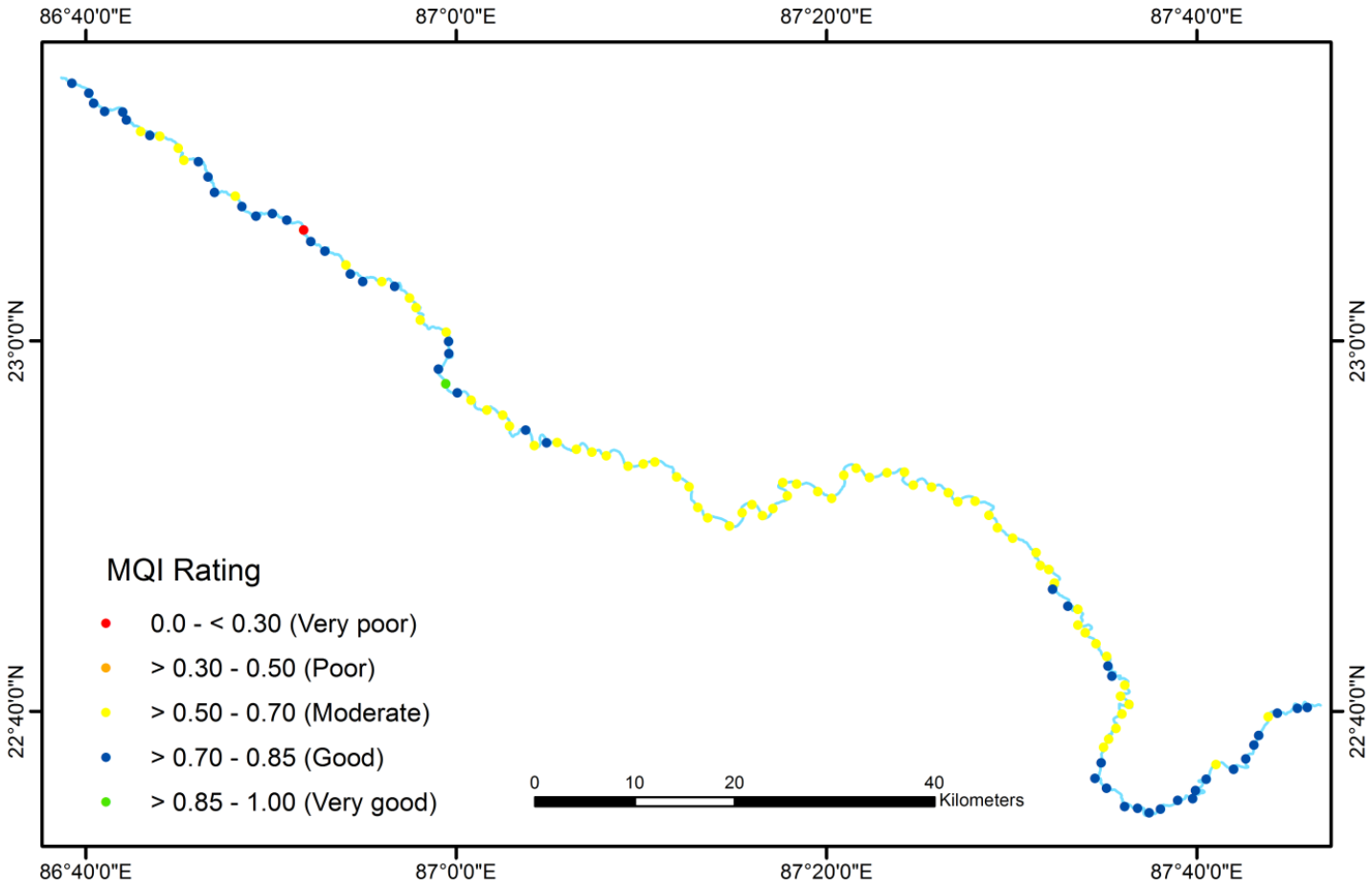


Fig. 8: Morphological Quality Index (MQI) calculated for the surveyed sites

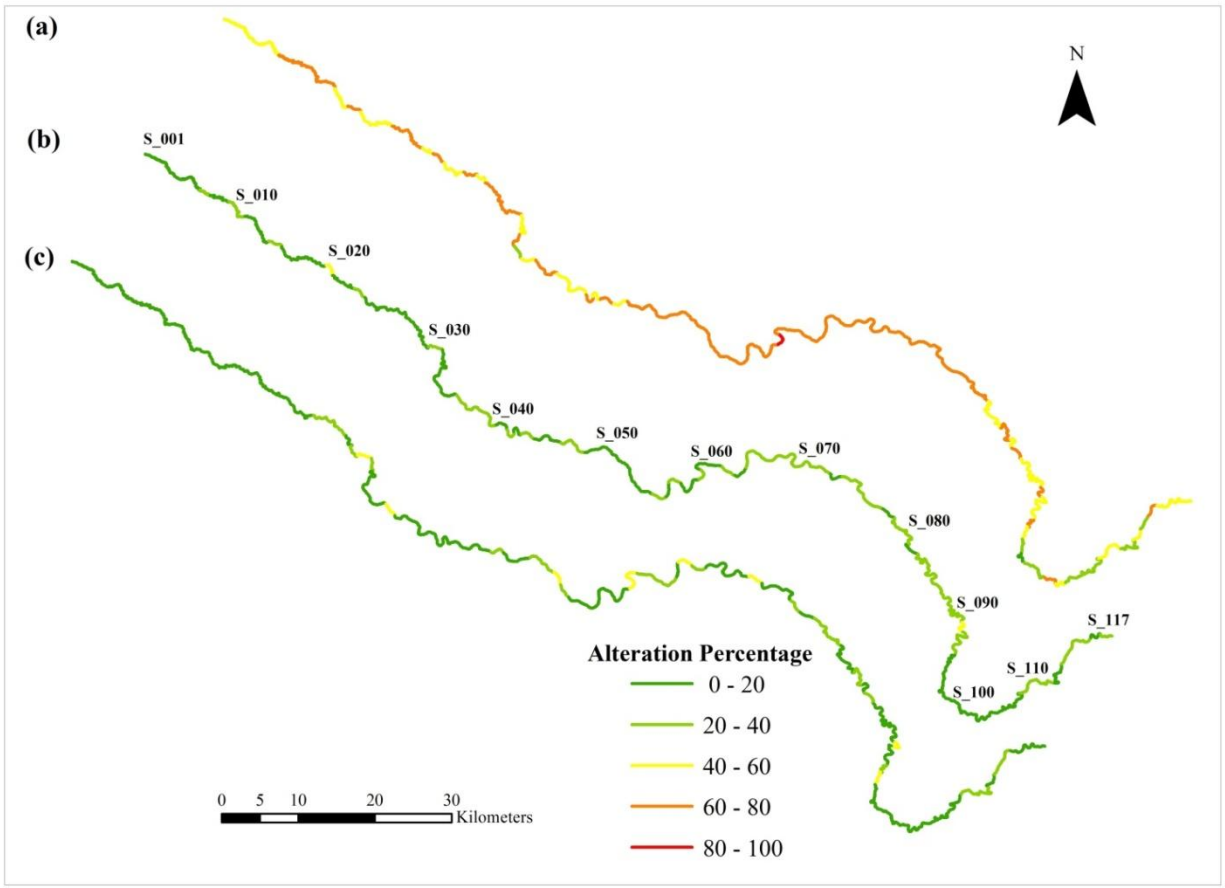


Fig. 9: Vertical Alteration- (a) channel functionality (b) artificiality and (c) channel adjustment

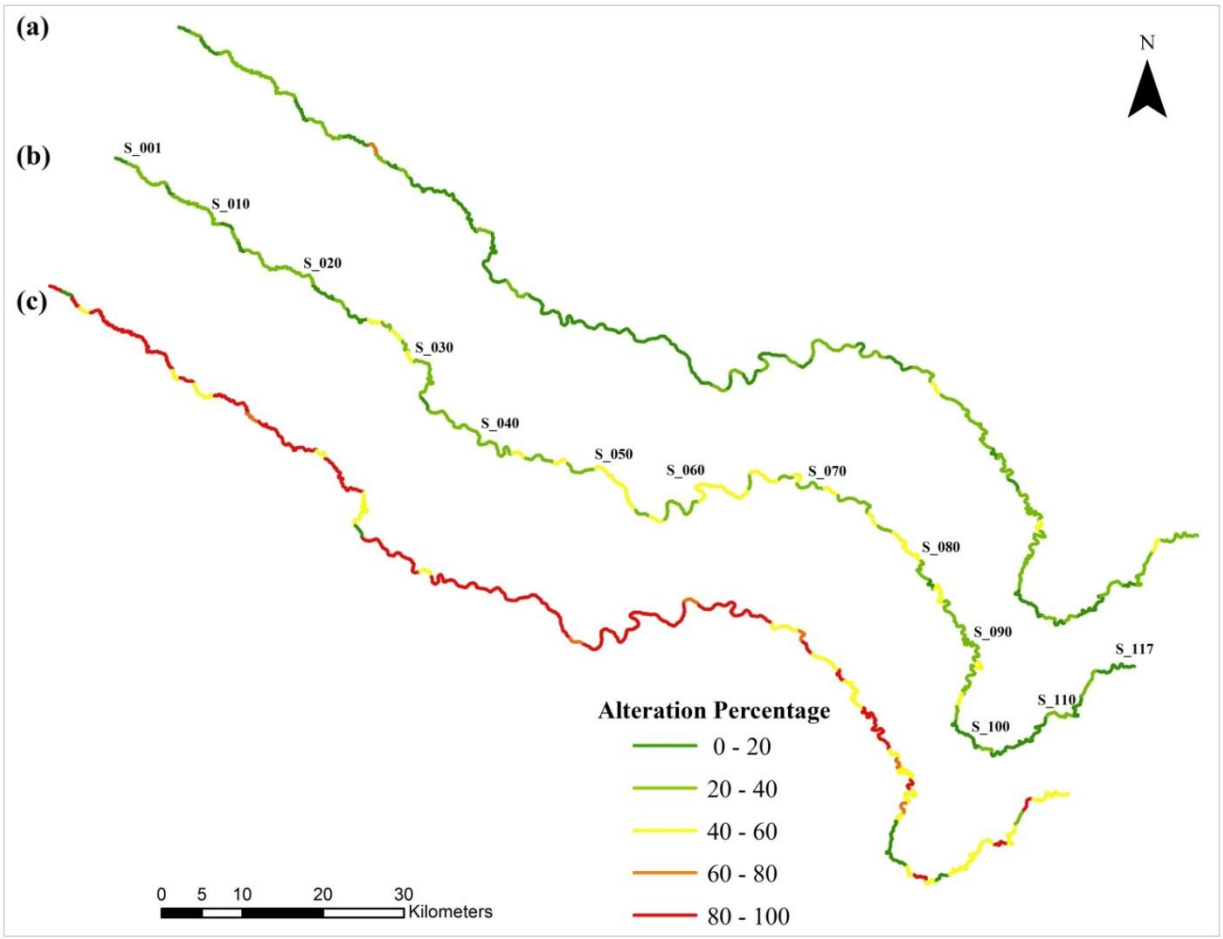


Fig. 10: Horizontal Alteration- (a) morphology, (b) channel continuity and (c) vegetation changes

This variation in riparian quality can be attributed to the increased intensity of human interferences, especially in the middle reaches and its consequent effects on channel adjustments, while the upper course retains its naturalness in a few headwater sites. Alteration is high throughout the middle stretch over the alluvial plains and the river becomes a prime site for sand mining activities, which creates deep hollows and pools (1.5-2 m deep), causing natural flow disruption and high turbidity, with significant degradation in stream biota and water quality. Crossing structures like bridges and a dense road network (metalled and unmetalled) leading to the channel by clearing much of the riparian vegetation to facilitate mining activities is another cause of riparian health impairment. Degraded stream quality in the lower course is mostly due to high embankments along the channel which make it narrow and constrained, causing siltation and reduced carrying capacity with resultant annual floods, bank slumping and consequent addition of sediments into the channel. The few sites that show better morphologic conditions are mostly less accessible by transport and thus retains much of the riparian vegetation.

With an average WQI score of 83.4 and classed as 'Very Poor' according to the Chatterjee & Raziuddin (2002) scale (Fig. 12), direct correlation exists between degrading water quality and impaired channel morphology. The main sand mining sites in the middle course (Fig. 12a) report higher turbidity that obstructs light penetration and thereby lowers DO levels (Fig. 12b). The deep pools (1.5- 2 m) created by bed scalping often get disconnected from the main flow forming stagnant zones in the active channel, housing algal blooms that further lower DO concentration, causing changes in in-stream species abundance, especially fishes. These zones are also characterised by higher water temperatures due to the combined effects of higher turbidity and lack of streamside shade from tree felling. This also reduces DO levels to below desirable limits, with values typically ranging between 2.3- 4.53 mg/l. These sites also have higher TDS values because of greater surface runoff generation from the bare riparian corridors, although the pH remains mostly within the permissible limit for the entire length of the channel. Effluents of domestic sewage from larger settlements like Ghatal together with phosphates and nitrates from agricultural runoff primarily lower water quality in the downstream reaches. River banks are sometimes used as dumping grounds, e.g. at Banka (S_087), which is also a river gauge station.

Degrading channel morphology was directly correlated with the reduced riparian vegetation cover (Fig. 13). In terms of total riparian quality, QBR scores for the entire Silai range between 15 (Kadam Deuli) to 90 (Tilabani and Kuldaha), average being 55 (fair quality). About 12% of reaches show good ecological condition with some disturbances present, 42% have fair or moderate riparian quality with important disturbances present, another 42% indicate the presence of strong alterations and possessing poor quality and about 4% having extremely bad quality with strong evidence of extreme degradation.

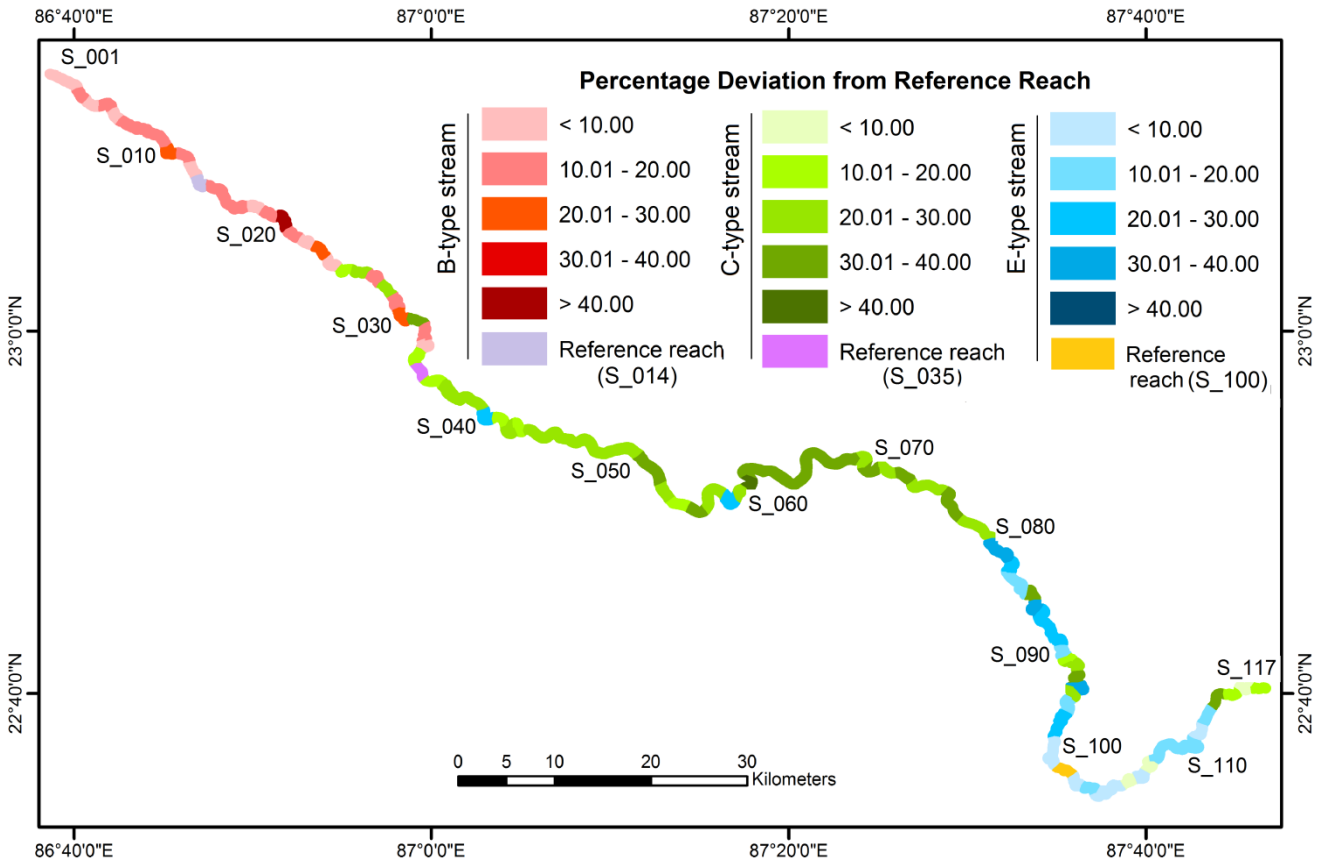


Fig. 11: Deviation of morphological quality from the Reference Reach for each stream type

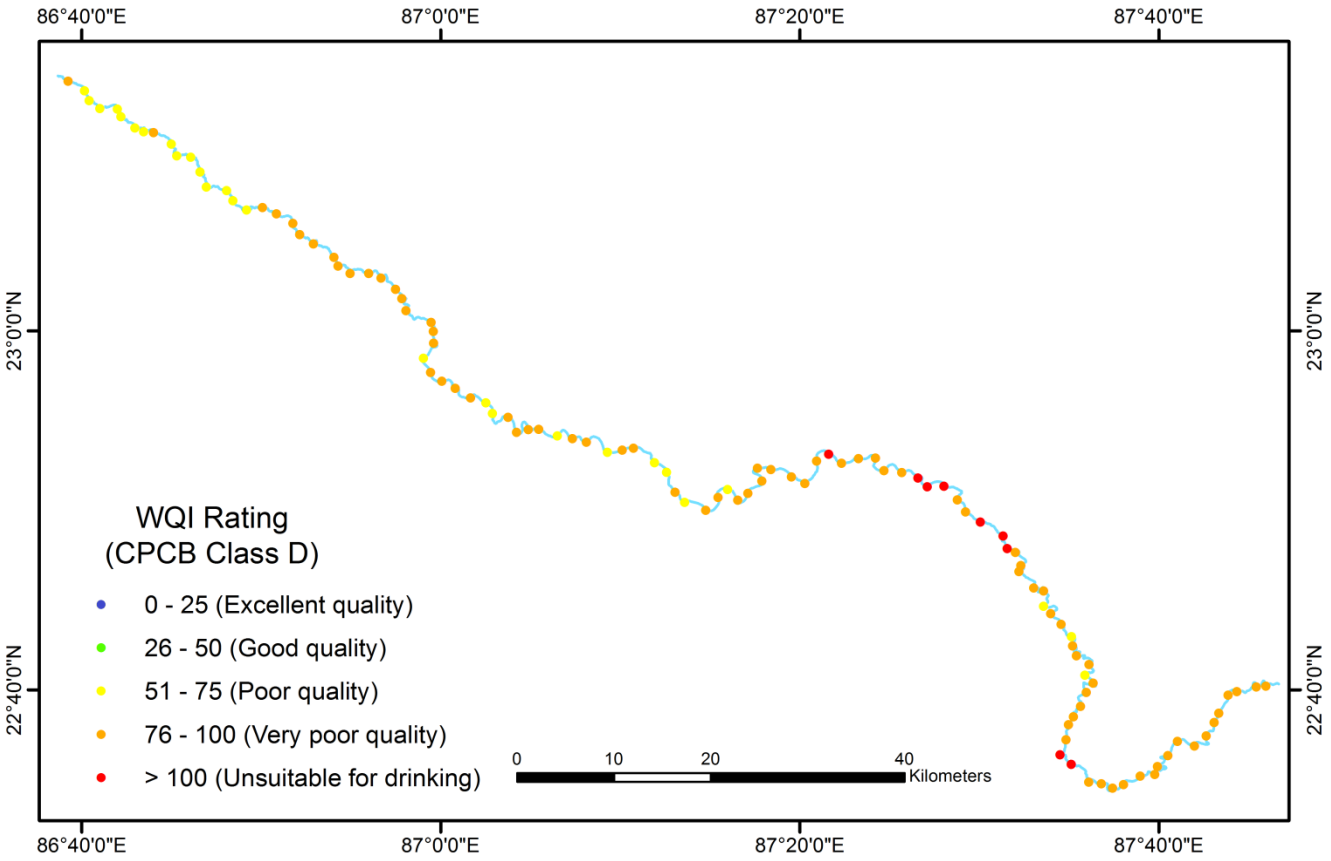
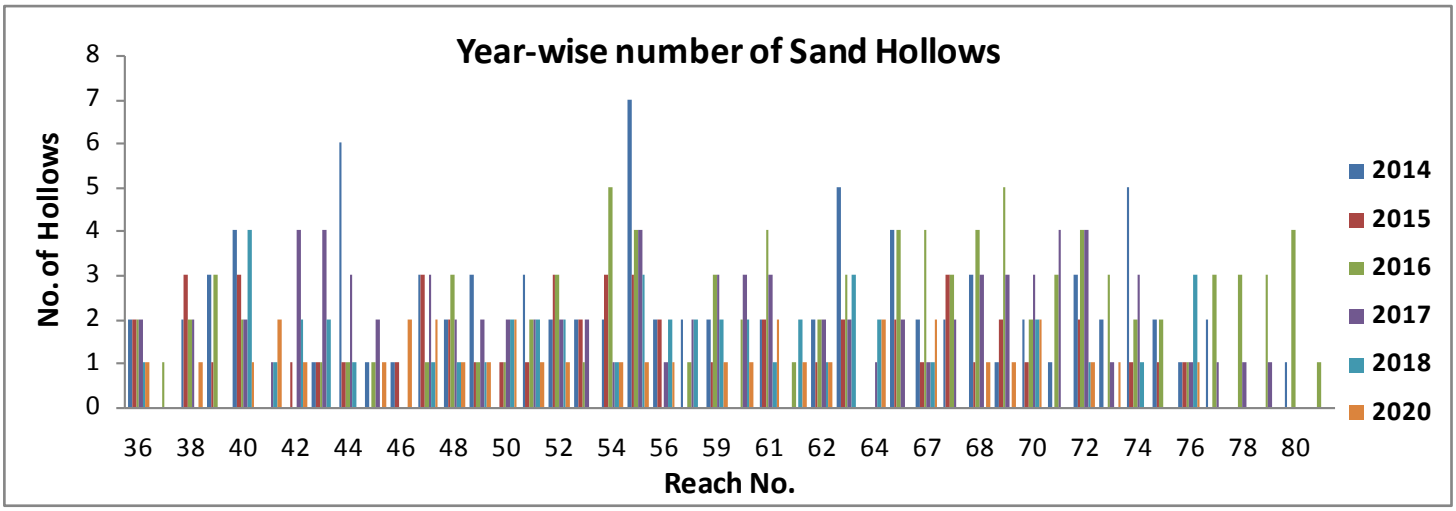
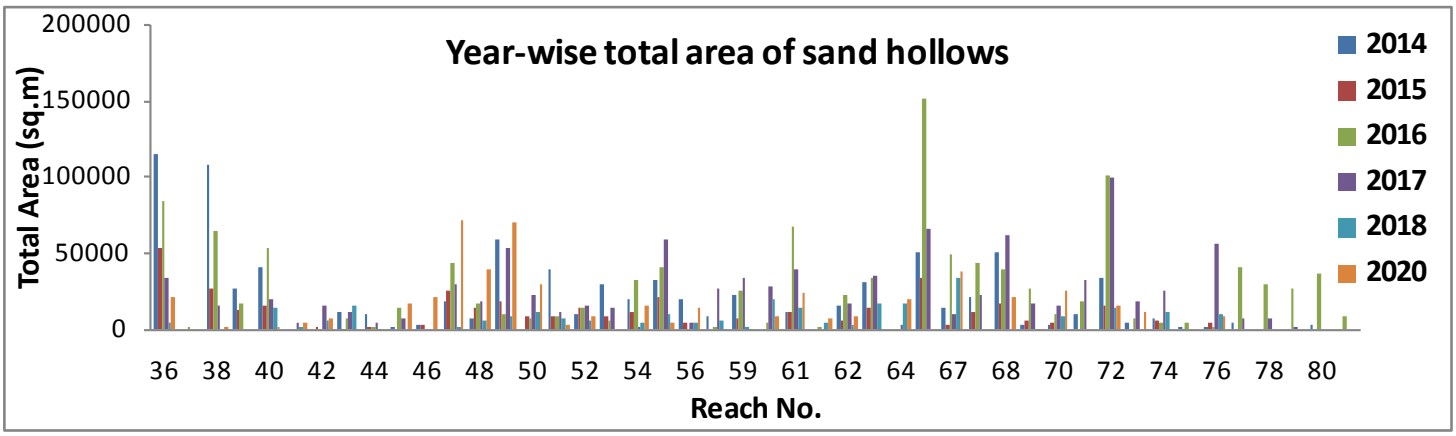


Fig. 12: Overall water quality along the main channel





Measured channel widths in different years with notable increase after sand-mining initiation

Site	2003	2007	2011	2015	2017	2018	2019	2020
46		181.51	159.51	164.77	158.95	168.59	175.07	184.53
47		216.61	218.24	223.51	212.91	216.36	232.1	235.75
47		197.81	199.66	205.57		200.41		226.1
48		119.03	120.6	127.69		129.32		141.25
49		178.82	181.58	195.94	210.5	208.96		219.46
50		221.55	228.37	229.8	249.41	250.95		267.91
52		170.27	160.29	154.15		156.72		172.19
57		152.14	147.83	148.8	145.62	141.49	144.48	159.14
60	179.98		137.67	157.15	177.82	174.65	177.59	185.73
62	179.18		163.92	177.76	177.43	179.38	185.83	191.89
63	193.38		190.41	171.29	172.45	173.44	175.83	186.66
64	14.81		136.81	116.96	127.5	121.04	121.85	130.17
67	136.16		119.39	125.99	126.44	126.96	141.52	
70	127.47		123.47	116.22	119.58	120.41		
76	88.45			66.15	74.53	85.43		
77	103.33	110.52		99.48	99.57	106.26		
85	26.79	28.03		22.91	21.86	26.99	29.35	

Thalweg position changes in select reaches as a result of sand-mining

Site	Shift from Previous Position (m)	Thalweg Shift Direction	Distance from Left bank (m)	Distance from right bank (m)	Mining site	Date	Date
50	223.0	Towards left bank	95.98		Towards mining site	24.01.2017	17.04.2020
61	89.5	Towards right bank		136.18	Towards mining site	13.12.2017	02.01.2020
65	103.0	Towards right bank		17.97	Towards mining site	18.01.2017	02.01.2020
71	87.4	Towards right bank		35.72	Mining from mid-channel	18.01.2017	25.12.2018
72	142.0	Towards left bank	25.76		Towards mining site	18.01.2017	25.12.2018

Fig. 12a: Sand mining sites along middle course of River Silai and their impact on the channel

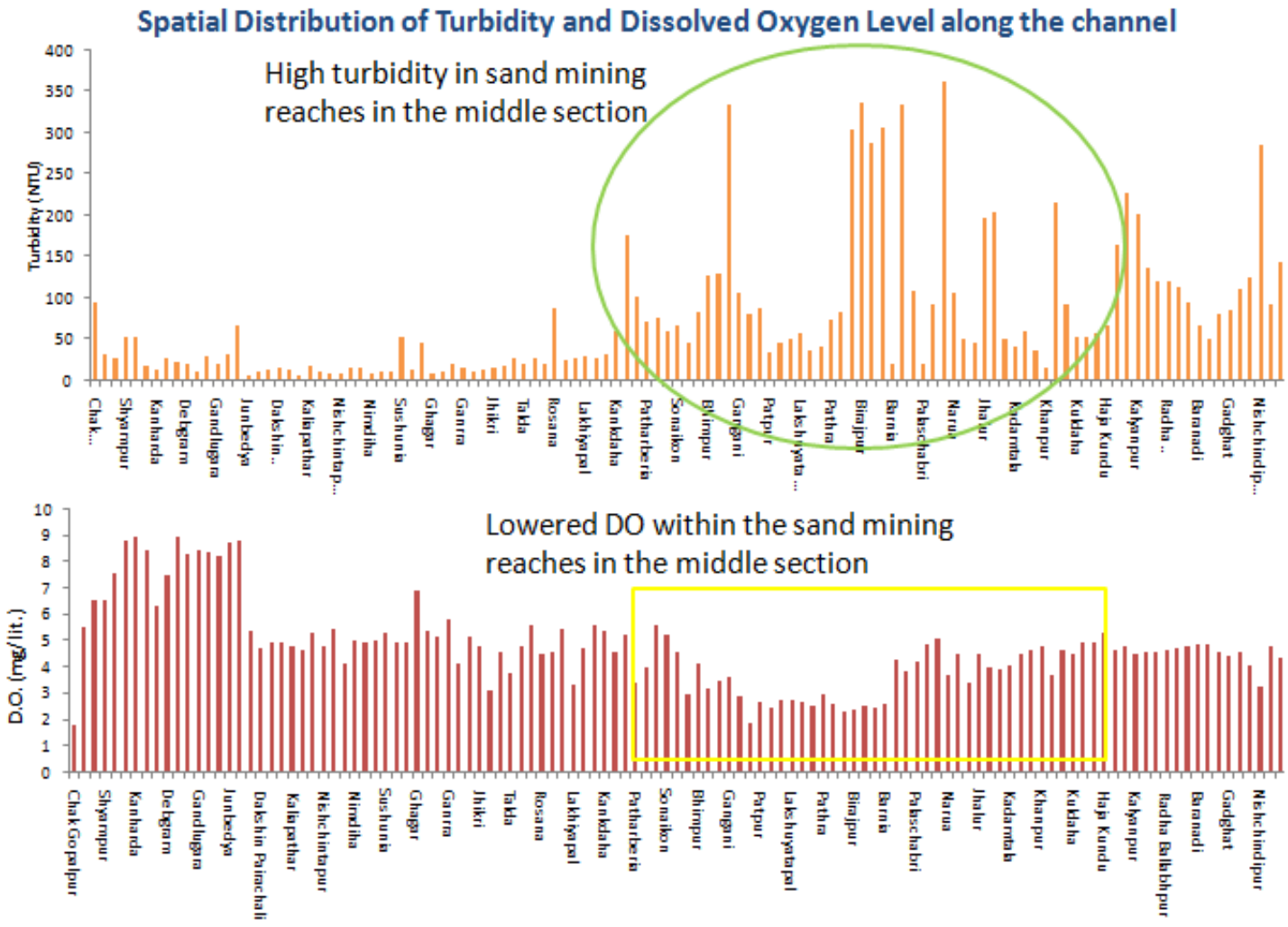

Spatial Distribution of Turbidity and Dissolved Oxygen Level along the channel
High turbidity in sand mining reaches in the middle section
Turbidity (NTU)
Lowered DO within the sand mining reaches in the middle section
D.O. (mg/lit.)

Fig. 12b: Heightened turbidity and lowered DO values in sand mining stretches

The RSQI was first calculated for a 500 m wide buffer as a whole and then again for the subdivided 10 zones of 50 m width each, on either bank (Fig. 15). While the overall 500 m RSQI recorded low variability, the first 50 m buffer, adjacent to the channel, accounted for much of the bank-line vegetation and recorded the site-specific vegetation cover changes. The average RSQI for the entire Silai for the 50 m buffer was quite low (RSQI = 36.03), with both banks taken together. While no reach attained the highest vegetation cover status, slightly higher values exist in the headwater zones. There the channel flows through undulating granitic plains and exhibits signs of slight entrenchment with the riverbed covered with boulders, gravels and scattered rock outcrops in some sections that restricts cultivation and the river's over-exploitation. The entire middle course has predominantly poor riparian quality as a result of agricultural ingress over the alluvial plains coupled with extensive sand mining following vegetation removal. The obtained results are further corroborated by the corresponding reach-wise mean NDVI values (Fig. 14) which showed similar results, i.e. the upper (0.23) and lower courses (0.29) having slightly higher vegetation cover and robustness than reaches along the middle stretch (0.19).

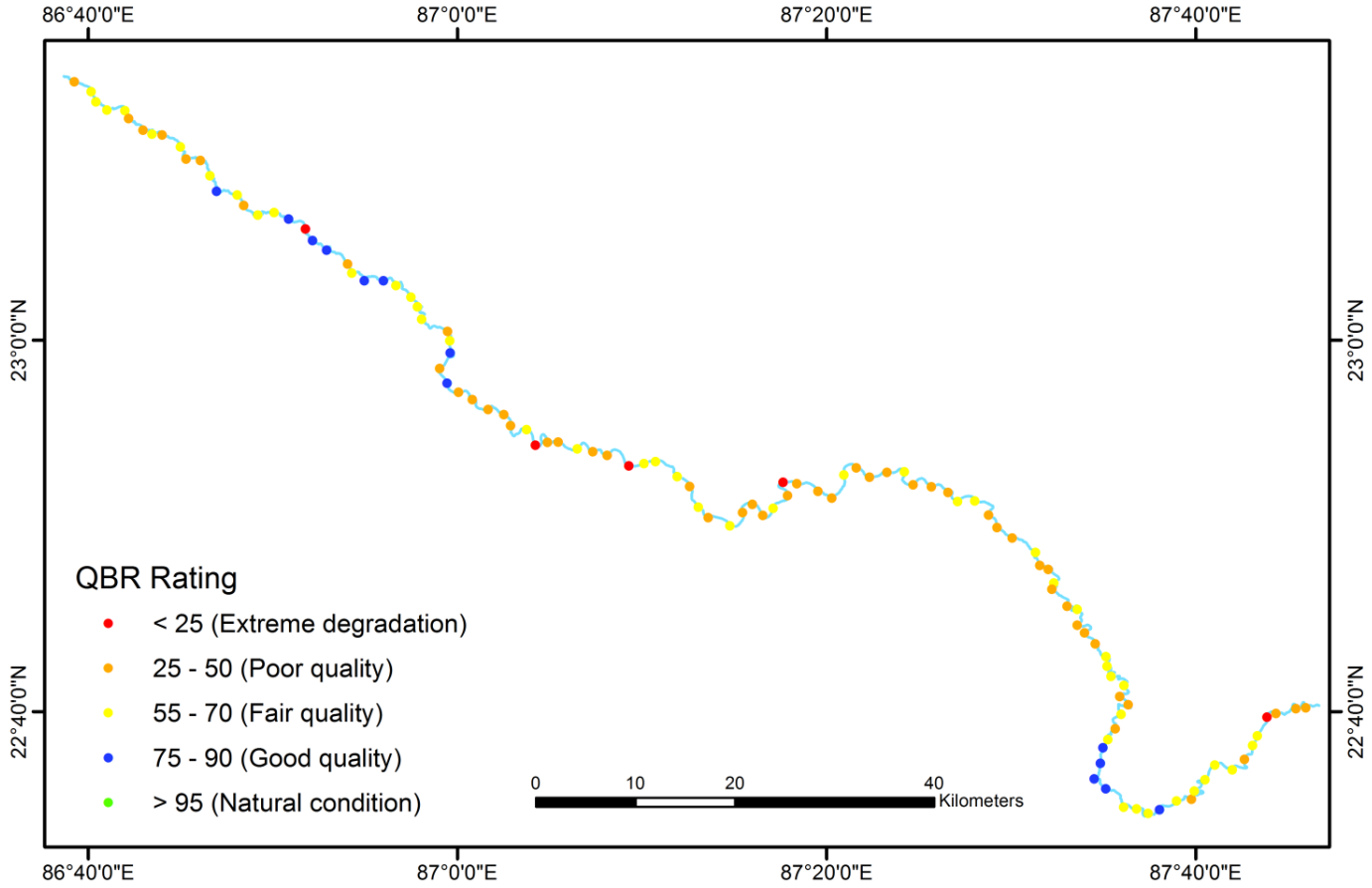


Fig. 13: QBR scores calculated along surveyed sites

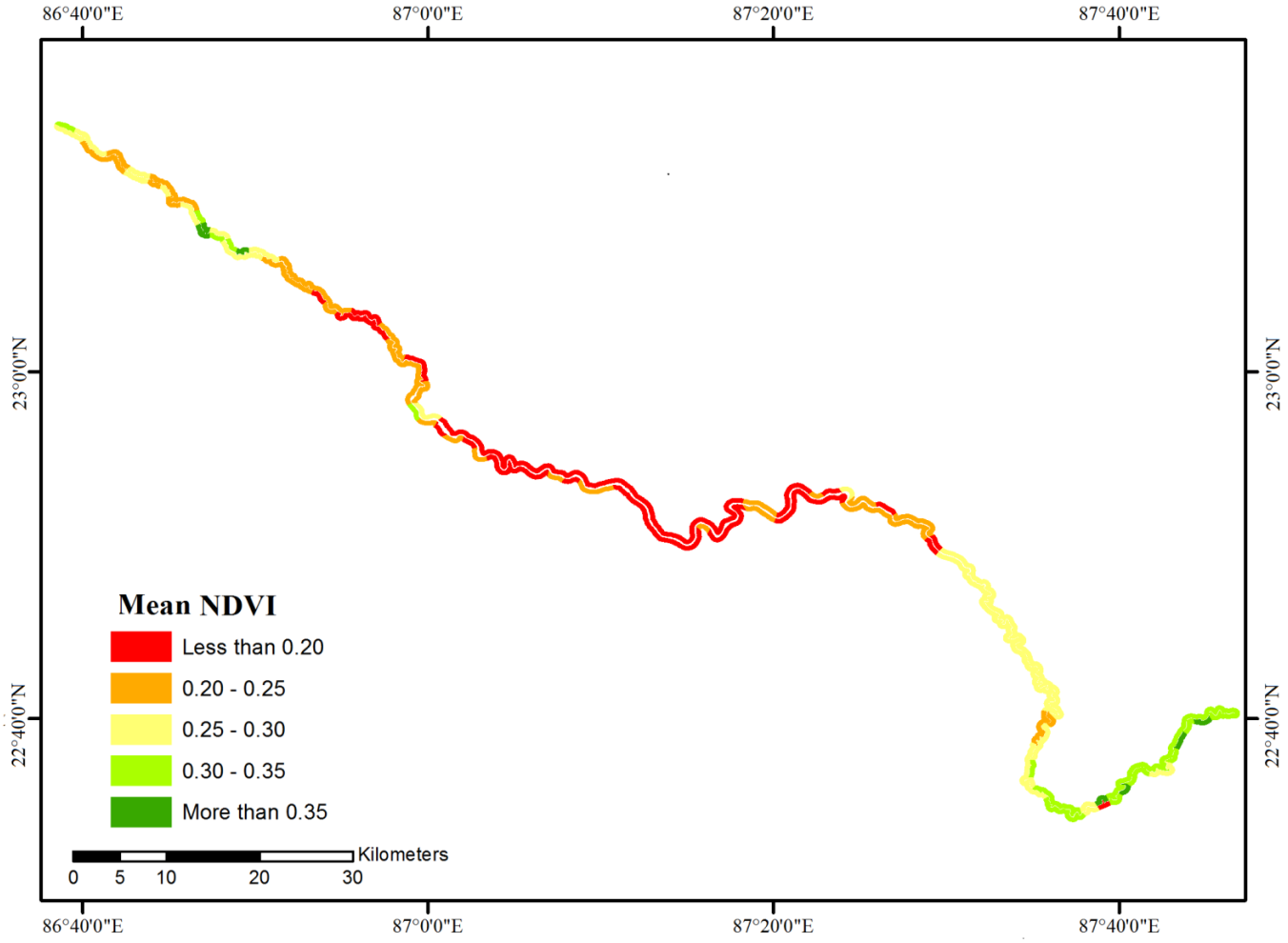


Fig. 14: Extracted NDVI values within the 50m corridor of the main channel

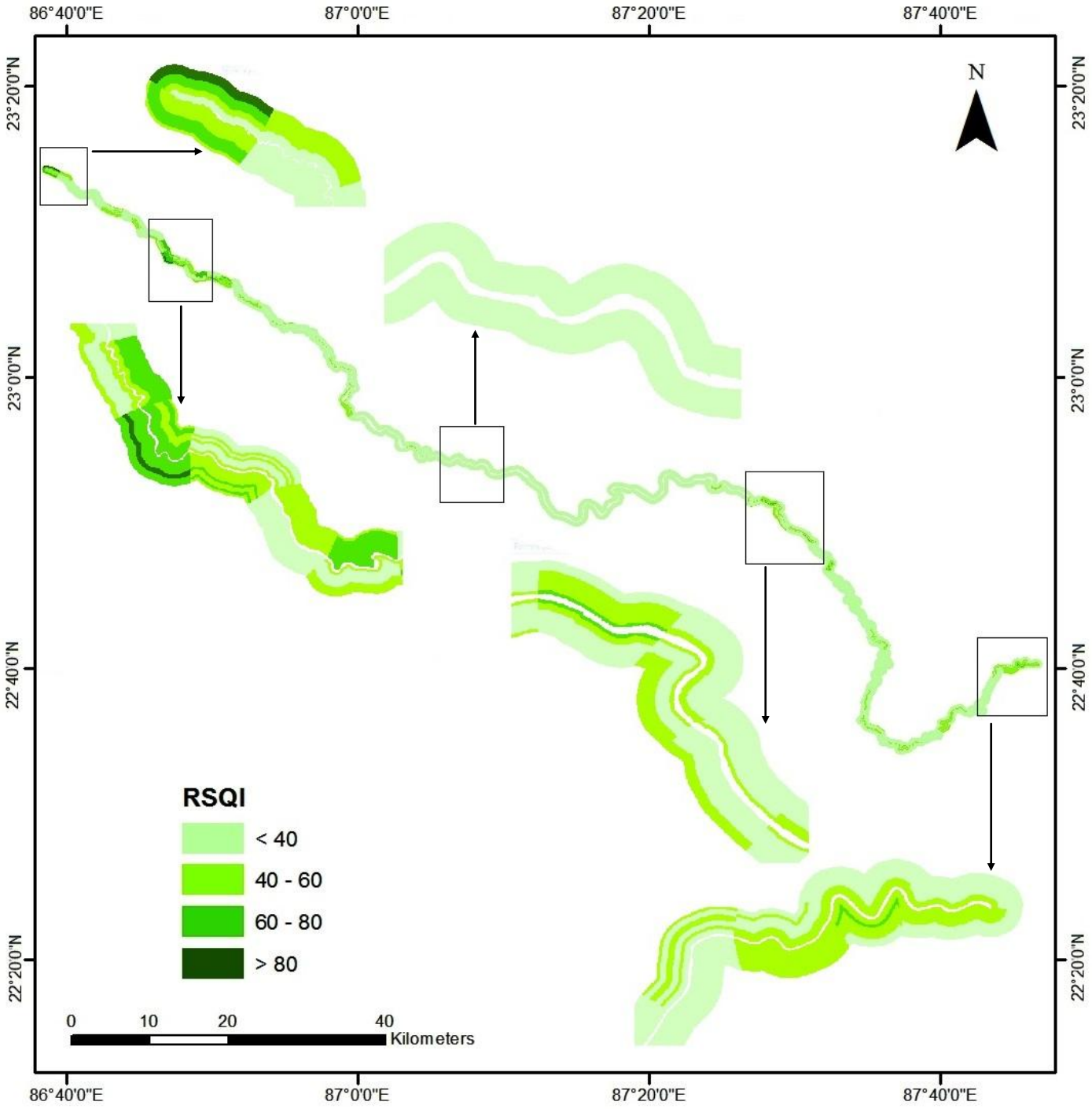


Fig. 15: Riparian Strip Quality scores calculated along the main channel for 50m buffer

As regards the overall stream quality (Fig.16), only one reach was classified as Category A, having naturally pristine morphological functions (0.85%), with it being located in the headwater zone. In all, 25 reaches displayed the most degraded condition, representing Category E (21.37%), mostly in the middle course, and these require high priority restoration. The other reaches fell into either Category B (17.95%), C (32.48%) or D (26.50%), again attesting that although some pristine reaches exist in upstream areas, most of the reaches show some form of alteration, whose intensity increases most in the middle and to a lesser extent in the lower course.

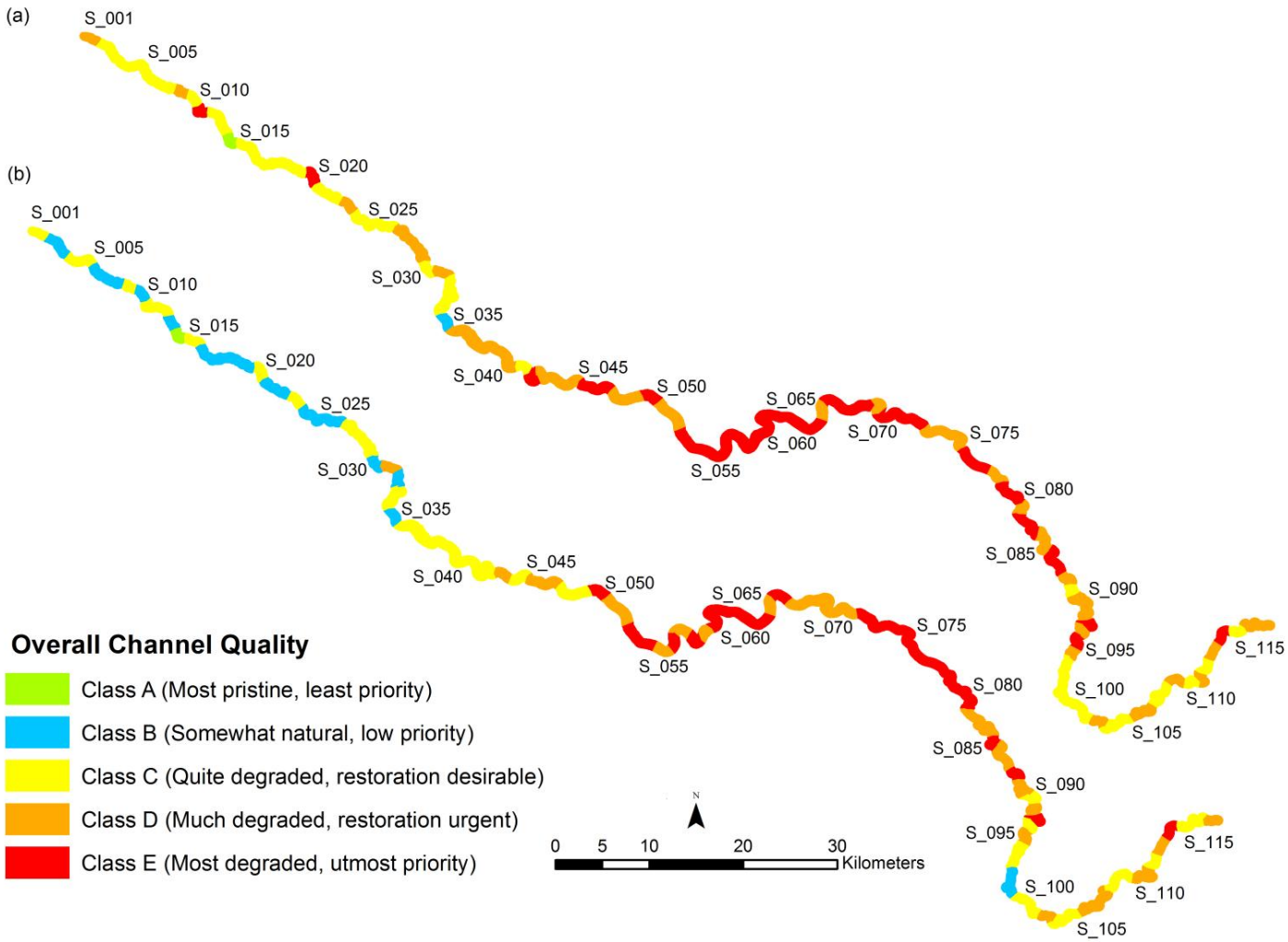


Fig. 16: Overall channel quality along the surveyed reaches- (a) combining the five indices, and (b) combining the five indices with turbidity and number of sand mining sites in each reach

What is apparent from the above analysis is that the stream morphological quality is intricately linked with its hydrological and ecological health (Fig. 16c). Such quality is seen to be particularly low for sites that have recorded low QBR and RSQI values (Table 1). Lateral channel continuity was seen to contribute towards a better morphological quality and was seen to depend directly on the naturalness of the riparian vegetation, which also allows habitat diversification and establishment of channel-floodplain linkages. Thus, a degrading riparian quality means disruption of the lateral channel continuity and thereby declining channel morphological functions. Most often, these were also the sites afflicted by unchecked sand mining activities and thus were characterised by lower DO and higher turbidity levels and an overall impaired water quality. This also highlights the direct relationship that exists between channel morphology and stream habitat, making it hostile for in-stream species to thrive. Channel slope could be directly linked to high morphological quality in a sense that steeper channel gradients consisting of gravel- and cobble-bed reaches indicated a greater potential for habitat

development and reflected a higher DO concentration and consequent higher morphological quality (Table 2). On the contrary, the sand-dominated reaches have shown lower DO levels in the disconnected pools, causing breaks in the longitudinal channel continuity thereby affecting natural channel morphology and causing habitat fragmentation. A declining vegetation cover was also seen to lower water quality by feasibly facilitating greater sediment addition into the channel, causing direct damage to in-stream species and in turn affecting the stream morphology and health. Therefore, the interdependence of each indicator in defining stream morphological quality once again points to the necessity of an integrated eco-hydromorphic approach that negates emphasis on any single component and instead provides a comprehensive overview of stream geomorphic health. To collate all the information together for each of the surveyed 117 reaches in a succinct manner, individual Site Cards were developed for each location (Fig. 16d). These can be used as a ready reference for each site and quickly provide its overview.

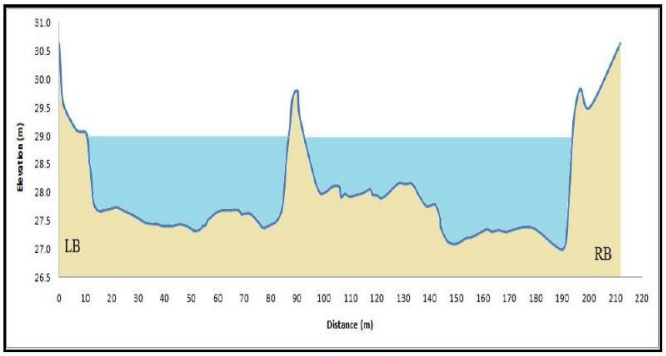
Rosgen Channel class	No. of Reaches	% length	Overall Quality Class				
			A	B	C	D	E
B1c	9	8.15	3	4	2		
B2c	2	1.81		2			
B3c	4	3.62		3	1		
B4c	6	5.43		6			
B5c	8	7.24	2	4	2		
C1	1	0.9			1		
C1c	1	0.9			1		
C3	1	0.9		1			
C4	2	1.81		1	1		
C4c	2	1.81		1	1		
C5	21	19.00		1	4	7	9
C5c	26	23.53			5	13	8
C6	1	0.9				1	
C6c	3	2.71			2		1
E4	1	0.9			1		
E5	24	21.72		3	7	8	6
E5b	2	1.81				1	1
E6	3	2.71			1	2	

Classes C, D & E require increasing levels of restoration measures as per priority

Fig. 16c: Stream type-wise reaches and channel quality class for the Silai River

Site No.: S072 **Lat/Long**: 22° 51′ 50.43″ N, 87° 26′ 37.15″ E
Location: Shyamanandapur, Garbeta-I, Paschim Medinipur
Lithologic setting: Reworked Lateritised Grit
Geomorphic setting: Upland Plains
USDA Soil Class: Fine Loamy Typic Ustifluvents
Dominant Bed/Bank Material: Sand
Channel Width (m): 131.81 **Floodplain width (m)**: 304.87
Mean Depth (m): 1.42 **Maximum depth (m)**: 1.94
Wetted Perimeter (m): 179.05 **Rosgen Class**: C5
L-Bank Height (m): 1.90 **R-Bank Height (m)**: 2.10
Rosgen Valley Type: Unconfined Alluvial valley (Type VIII)
Reach Slope (m/m): 0.0019 **Velocity (lean) (m/s)**: 0.434
Tributaries: Distributary **Discharge (m^3/s)**: 104.75
Tot. Strm Pow (W/m): 1950.45 **Shear stress (N/m^2)**: 26.47
MQI Score: 0.57 **MQI Class**: Moderate
QBR Score: 35 **QBR Class**: Poor Quality
RSQI Score: 25.8 **RSQI Class**: Very Low
Predominant LULC: Agriculture
Reach Mean NDVI: 0.21 **WQI Value**: 101.0
DO (mg/L): 2.5 **Turbidity (NTU)**: 42
BEHI Value: 46.09 (L-Bank) **Bank Erosion Class**: Extreme
Flood Occurrence: Annual **Embankment**: No
Sand mining sites: 3 **Crossing structures**: No
Prioritisation Score: 3.57 **Priority Class**: E (Most degraded)
Protection measures: No protection

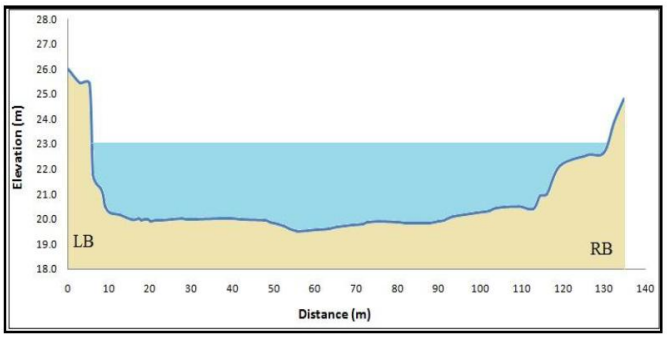
Site Name: SHYMANANDAPUR



Cross-sectional View

Site No.: S078 **Lat/Long**: 22° 48′ 37.09″ N, 87° 31′22.18″ E
Location: Keshadal, Chandrakona-II, Paschim Medinipur
Lithologic setting: Fine Sand Silt Clay
Geomorphic setting: Deeply Weathered Plains/ Duricrust
USDA Soil Class: Fine Loamy Ultic Paleustalfs
Dominant Bed/Bank Material: Sand
Channel Width (m): 79.07 **Floodplain width (m)**: 186.1
Mean Depth (m): 2.64 **Maximum depth (m)**: 3.45
Wetted Perimeter (m): 127.14 **Rosgen Class**: C5c
L-Bank Height (m): 3.50 **R-Bank Height (m)**: 4.20
Rosgen Valley Type: Unconfined Alluvial valley (Type VIII)
Reach Slope (m/m): 0.0005 **Velocity (lean) (m/s)**: 0.365
Tributaries: No **Discharge (m^3/s)**: 123.40
Tot. Strm Pow (W/m^2): 604.66 **Shear stress (N/m^2)**: 12.95
MQI Score: 0.63 **MQI Class**: Moderate
QBR Score: 60 **QBR Class**: Poor
RSQI Score: 31.7 **RSQI Class**: Very Low
Predominant LULC: Agriculture
Reach Mean NDVI: 0.29 **WQI Value**: 101.1
DO (mg/L): 2.5 **Turbidity (NTU)**: 307
BEHI Value: 49.64 (R-Bank) **Bank Erosion Class**: Extreme
Flood Occurrence: Annual **Embankment**: No
Sand mining sites: 5 **Crossing structures**: 2
Prioritisation Score: 3.71 **Priority Class**: E (Most degraded)
Protection measures: No Protection

Site Name: KESHADAL



Cross-sectional View

Fig. 16d: Examples of Site Cards designed for each surveyed location and reach

Table 1: Stream type-wise mean values of the hydrogeomorphic and ecological parameters

Type	**Segments**	**Sinuosity**	**ER**	**WDR**	**Slope** (m/m)	**MQI**	**QBR**	**WQI**	**DO** (mg/l)	**pH**	**TDS** (mg/l)	**Turbidity** (NTU)	**RSQI**	**NDVI**
B1c	9	1.47	1.79	27.31	0.0022	0.72	57.22	72.5	7.3	8.0	262	26	38.83	0.27
B2c	2	1.29	1.64	24.83	0.0014	0.73	70.00	83.2	5.1	7.8	273	16	37.50	0.26
B3c	4	1.27	1.84	23.36	0.0021	0.68	51.25	69.4	7.3	7.9	246	29	31.75	0.24
B4c	6	1.44	1.73	19.60	0.0023	0.70	60.00	73.8	6.5	7.9	304	25	35.25	0.24
B5c	8	1.43	1.93	24.91	0.0027	0.73	63.13	79.5	5.5	7.8	233	25	46.00	0.23
C1	1	1.21	3.07	32.26	0.0028	0.77	50.00	72.2	7.0	7.9	190	8	49.50	0.24
C1c	1	1.20	2.66	25.03	0.0010	0.61	65.00	93.4	5.0	8.2	220	9	58.50	0.21
C3	1	1.23	2.48	26.12	0.0010	0.64	75.00	91.9	5.5	8.3	230	16	45.50	0.19
C4	2	1.20	3.13	38.04	0.0016	0.74	60.00	79.8	5.6	7.9	198	14	50.50	0.24
C4c	2	1.47	2.91	36.30	0.0005	0.71	60.00	88.3	4.5	7.9	215	10	37.00	0.20
C5	21	1.38	2.59	29.09	0.0018	0.62	47.62	89.1	3.8	7.7	139	111	31.14	0.20
C5c	26	1.44	2.96	29.13	0.0005	0.64	49.23	85.8	4.0	7.6	143	80	33.44	0.22
C6	1	1.21	2.36	13.99	0.0020	0.75	50.00	84.7	4.4	7.7	160	145	42.00	0.30
C6c	3	1.35	2.66	17.50	0.0012	0.70	35.00	85.9	4.1	7.7	167	169	41.67	0.33
E4	1	1.64	3.22	37.94	0.0010	0.65	35.00	74.8	4.8	7.4	153	16	25.00	0.20
E5	24	1.49	3.94	7.75	0.0011	0.70	57.91	85.6	4.4	7.8	206	116	37.54	0.29
E5b	2	1.65	3.23	14.91	0.0006	0.64	50.00	79.4	4.9	7.6	170	59	31.00	0.23
E6	3	1.43	3.20	10.91	0.0002	0.74	53.33	85.5	4.5	7.8	157	94	26.83	0.34

Table 2: Correlation between the different hydrogeomorphic and ecological parameters derived reach-wise for the Silai River

	Sinuosity	Entrenchment Ratio	Width/Depth Ratio	Slope	MQI Score	QBR Score	WQI	DO	pH	TDS	Turbidity
Sinuosity	1.00										
Entrenchment Ratio	0.28	1.00									
Width/Depth Ratio	-0.11	-0.08	1.00								
Slope	-0.35	-0.55	0.14	1.00							
MQI Score	-0.25	-0.12	-0.09	0.43	1.00						
QBR Score	-0.38	-0.33	0.00	0.06	0.06	1.00					
WQI	-0.20	0.29	-0.15	-0.58	-0.39	0.28	1.00				
DO	-0.22	-0.49	0.20	0.65	0.32	0.25	-0.76	1.00			
pH	-0.60	-0.29	0.04	0.15	-0.01	0.76	0.25	0.44	1.00		
TDS	-0.17	-0.67	0.00	0.42	0.21	0.65	-0.32	0.67	0.57	1.00	
Turbidity	0.07	0.26	-0.63	-0.18	0.01	-0.52	0.32	-0.61	-0.42	-0.56	1.00

Chapter-4 — Riparian Hazards along a Lowland River

This chapter focuses on analysing the causes of channel health impairment by identifying the major fluvial hazards that inflict these reaches which has been explained with the help of a flowchart (Fig. 17). Four main fluvial hazards have been identified that cause stream health degradation in the said reaches. While the middle course is seen to be heavily inflicted by massive illegal sand mining activities that tend to cause channel and bank instability, annual flooding causes havoc mainly in the downstream reaches of the channel. Associated with flooding, is the problem of bank instability which also tends to wash out tracts of fertile cultivable land causing economic losses in the region.

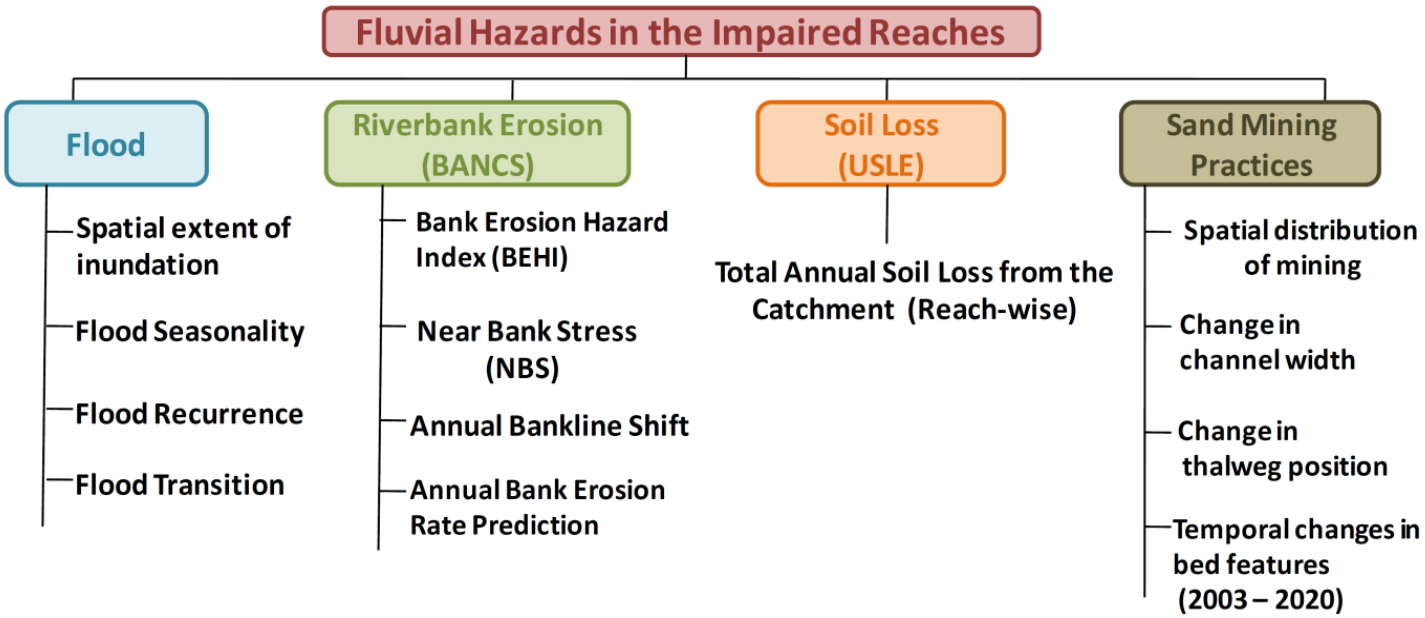


Fig. 17: Flowchart depicting the methodology followed in this chapter

Sand mining hazard

The spatial distribution of the present sand mining sites has been quantified and mapped using Google Earth Pro and ArcGIS 10.2.2, along with its temporal analysis (2003-2020) to highlight the changes in channel planform and morphology caused by it over this period. The number of sand hollows and pools, their depths, length of tyre marks of tractors/trucks on sand bars, changes in channel width and thalweg positions near mining sites and loss of channel connectivity have been measured and represented with the help of suitable cartograms. The specific impact of sand mining on channel morphology was examined in the representative Garbeta reach (S_064), where natural sandbars that were present in 2003 have been vigorously mined, resulting in flow bifurcation and fragmentation of the bars. A steady increase in the mined

bar area was observed with eventually no bars existing in 2020, which highlights not only the channel morphological changes but also alterations in the riverside vegetation (Fig. 18).

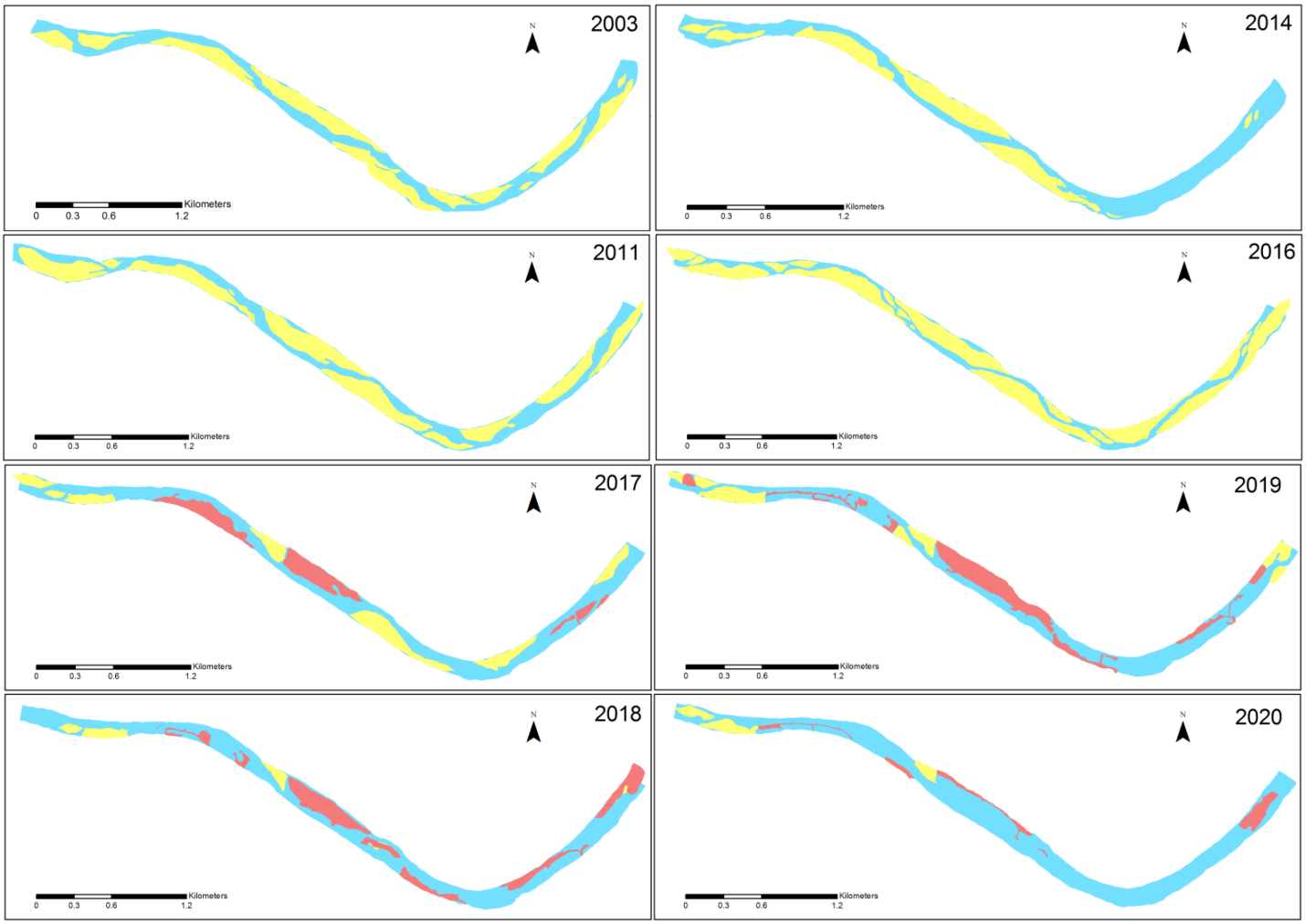


Fig. 18: Bar removal and changes in channel morphology due to sand mining at Garbeta

Flood hazard

The flood extent map (Fig. 19) was extracted from the European Commission Joint Research Centre's Global Surface Water dataset. Almost the entirety of Ghatal Block on the left bank of the river is flood-prone with the right bank being less affected due to the circuit embankment along the southern part of Chandrakona-I and Daspur-I Blocks and the south eastern part of Keshpur Block. The low elevation (3-5 m amsl on average) of the region coupled with the river being on higher ground than its surrounding floodplain causes water stagnation for periods of up to four months. The annual inundation duration and seasonality assumes particular importance as it alters landuse patterns during the monsoons when the stranded water is used for pisciculture. Yearly inundation duration (Fig. 20) reveals that parts adjacent to the left bank remain inundated for at least a month after the peak flood flow has receded, while even lower elevation zones retain floodwaters up to 2-3 months. Of utmost importance is the flood transition

map (Fig. 21) which depicts changes in the seasonality of three main water classes (permanent water, seasonal water and no water) in the region. Although no new parcel of land has been declared as permanently flood affected in the region, the percentage of seasonal water coverage has increased in the region with new seasonal water surfaces indicating a conversion of land into seasonal water and also conversion of water back into land surfaces, which indicates continued inundation depending on the severity of monsoon.

Riverbank erosion and bank failure hazard

The spatial extent and nature of bank erosion in the region has been examined using the Bank Assessment of Nonpoint Source Consequences of Sediments (BANCS) Model to calculate the short term bank erosion rate. A total of 55 sites (with their left and right banks considered separately) spatially distributed over the middle and lower courses of the Silai that showed clear signs of bank slumping and collapse during the field surveys were analysed. This model uses three main aspects of erosion, i.e. bank erodibility which is represented by the Bank Erosion Hazard Index (BEHI), bank erosivity estimated by the Near Bank Stress (NBS) and its associated energy distribution along streambanks and the historical bankline shift to predict the annual rate of bank erosion and the volume of sediment lost from a site.

The overall observed BEHI values primarily range between high (20.00%), very high (34.55%) and extreme (40.91%) (Figs. 22a, 22b) as only those sites were included in the analysis that had visible signs of erosion during the field visits. The left bank however showed higher probability of erosion due to their characteristically steep high banks and higher bank angles that are most often devoid of vegetation. As regards the NBS, the erosive power of water has been seen to be ranging between moderate to low, i.e. 59.09% of the reaches recording low NBS scores with the left bank showing further lower NBS than their right counterparts (Figs. 23a, 23b). Recent bankline shift rates (2017-2020) have also followed a similar trend with the right bank showing a greater average shift (3.41 m/yr) than the left (1.61 m/yr). Such shifts in banklines were greater along the middle course where the major sand mining sites are located. Further downstream, both BEHI and NBS recorded low to moderate values and consequent lower shifting rates partly because these sites show minimum sand mining and therefore much of the natural riparian vegetation has been kept intact there. Also, towards the lower course, the predominance of clay having higher bulk density and higher failure thresholds reduces soil erodibility (Sass & Keane, 2012). Furthermore, the low inter-particle spaces of clay tend to hold soil particles together better than sand and therefore are less susceptible to swelling and erosion upon wetting. The predicted annual erosion rate was estimated to be around 2.15 m/yr for the reaches showing high to very high erosion potential. The short-term predicted bankline shift rates

for both the left and rights banks were ascertained using the combined parameters of BEHI, NBS and bank shifting rates (Figs. 24a, 24b). The trend lines plotted on these values (Fig. 25) elicit bank shift rates between 1 - 5 m/yr along different parts of the river. Higher rates (3-5 m/yr) are mostly seen in the middle stretch of the river, along the sand mining sites, attesting to their deleterious role in increasing the channel instability. These sites should be considered as primary restoration spots using suitable bioengineering measures.

Mean annual soil loss

Soil loss from the catchment is another important determinant of stream health. It was estimated using the Universal Soil Loss Equation (USLE) using the standard formulae (cf. Majhi et al. 2021). The individual factors (Fig. 26) were ascertained first from different relevant datasets (Table 3) and then multiplied to obtain the mean annual soil loss across the basin (Fig. 27). The zones most affected by soil loss have been further analysed using grid overlays of 1 km × 1 km to identify sites where management strategies such as grass buffers can provide some relief (Fig. 28). Here, soil loss has been taken as a proxy for runoff, as higher runoff usually indicates a greater amount of soil loss. To further pinpoint sites for installing grass buffers, consecutive 50 m wide strip-wise enumeration of the soil loss was done for all the streams in the basin (Fig. 29). The southern and south-eastern portions are seen to be the most affected stretches in this respect.

Table 3: Methods used to compute individual factors for the USLE

USLE factor	Formula	Method and data used
R factor (rainfall erosivity)	Babu et al. (2004)	$R = 81.5 + 0.38P$ P: annual precipitation (mm); Original unit: t-m cm ha^{-1} h^{-1} yr^{-1}. Computed SI unit: MJ mm ha^{-1} h^{-1} yr^{-1} (above result is multiplied by 10.204 to convert to SI units). Input data was 19 years (2000-2018) monthly gridded rainfall data from WorldClim repository.
K factor (soil erodibility)	Sharpley and Williams (1990)	$K = \left[0.2 + 0.3exp\left(-0.0256SAN\left(1 - \frac{SIL}{100}\right)\right)\right] \times \left[\frac{SIL}{CLA+SIL}\right]^{0.3} \times \left[1.0 - \frac{0.25\,C}{C+exp\,(3.72-2.95C)}\right] \times \left[1.0 - \frac{0.7\,SN1}{SN1+exp(-5.51+22.9\,SN1)}\right]$ SAN, SIL, CLA and C are percentages of sand, silt, clay and organic carbon contents respectively, and SN1 is SAN divided by 100 and subtracted from 1. Imperial units: t acre h 100-$acre^{-1}$ ft^{-1} $tonf^{-1}$ $inch^{-1}$. Computed SI unit: t ha h ha^{-1} MJ^{-1} mm^{-1} (above result is multiplied by 0.1317 to convert to SI units). Data for this was used from soilgrids.org
LS factor (slope length and steepness)	Moore and Burch (1986)	$LS = \left(\frac{As}{22.13}\right)^{0.4} \times \left(\frac{\sin\theta}{0.0896}\right)^{1.3}$ As: unit contributing area; θ: slope angle; As = flow accumulation × DEM cell size. Thresholding of the flow accumulation has been done to only take slope lengths below 120 metres long (usual limit of overland flow). Input data for this was the geoid corrected ALOS PALSAR 12.5 m DEM.
C factor (cover and land management)	Collated from different studies	These values for the study area have been taken as Forest - 0.003; Plantation - 0.13; Orchard - 0.4; Scrub/Fallow - 0.5; Barren Lands - 1.0; Paddy croplands - 0.2; Waterbodies - 0.0; Settlements - 0.0. Data for this was based on the Land Cover Land Use Map prepared under India Biodiversity System by IIRS, Dehradun.
P factor (support practice)	Taken uniformly throughout	P = 1 (for lands that are mostly paddy cultivated and have not clear soil erosion management aspect like contour ploughing, terrace cultivation).

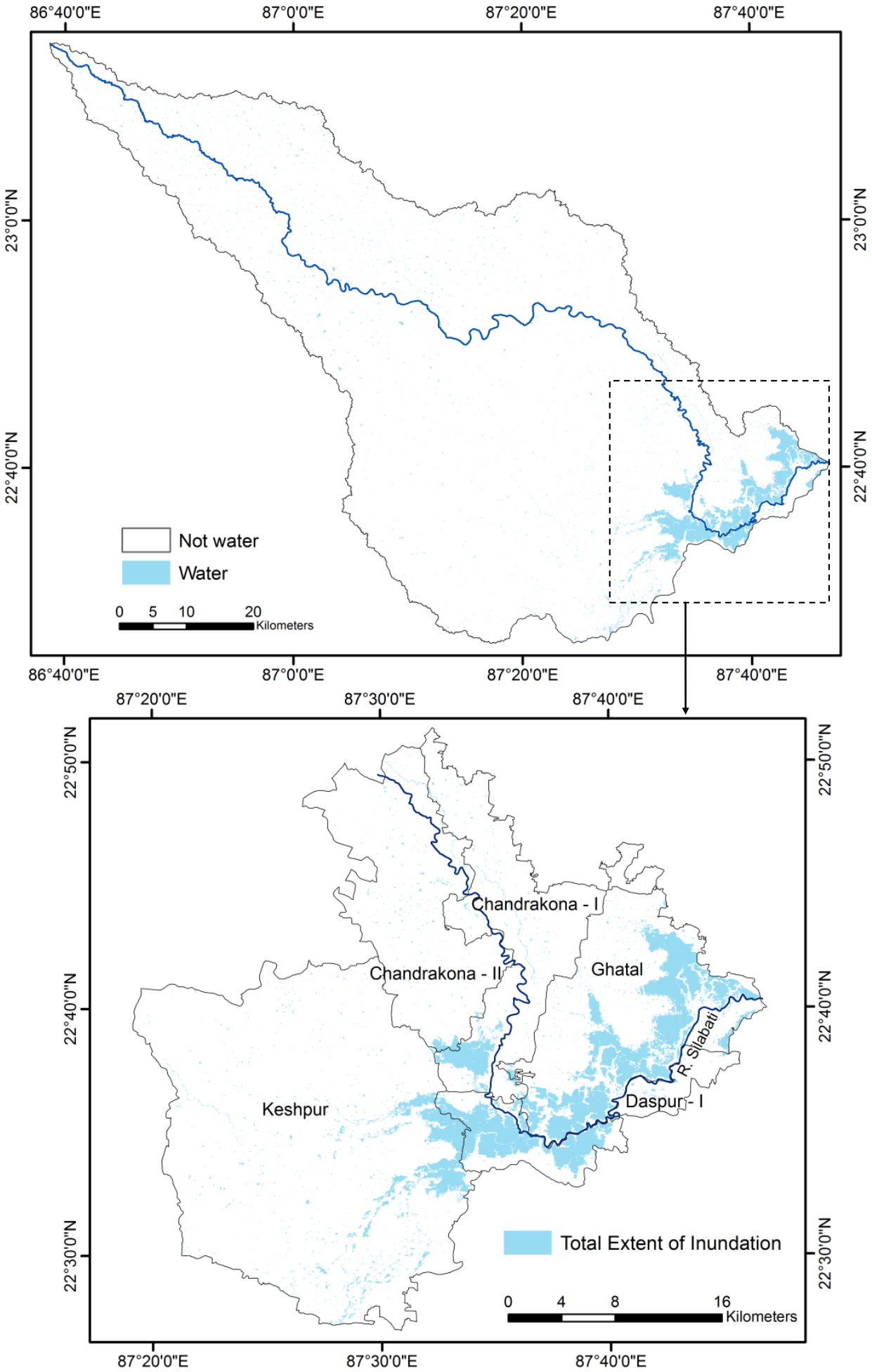


Fig. 19: Inundation extents in the downstream section of the channel

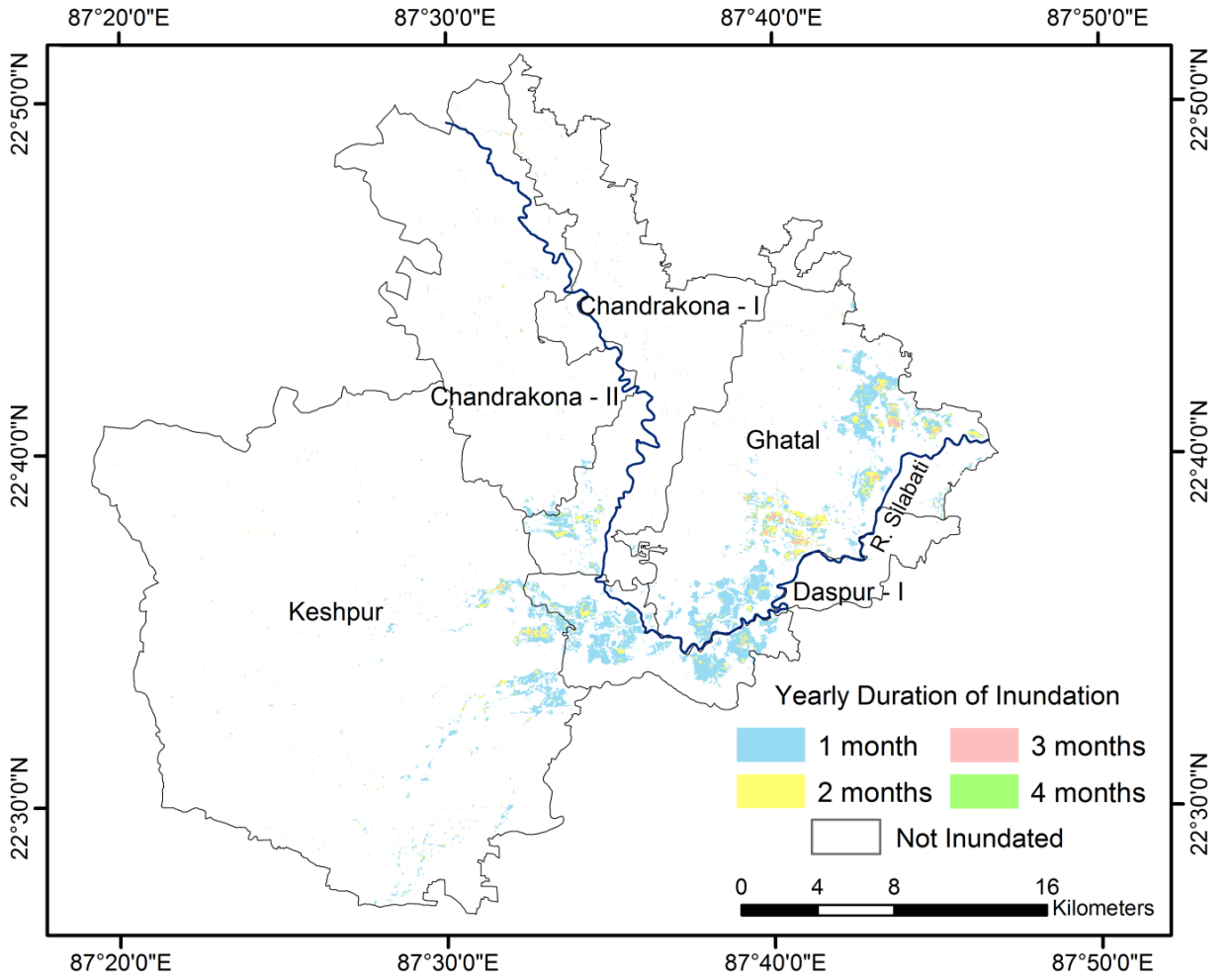


Fig. 20: Map showing areas of yearly inundation duration in the flood affected regions

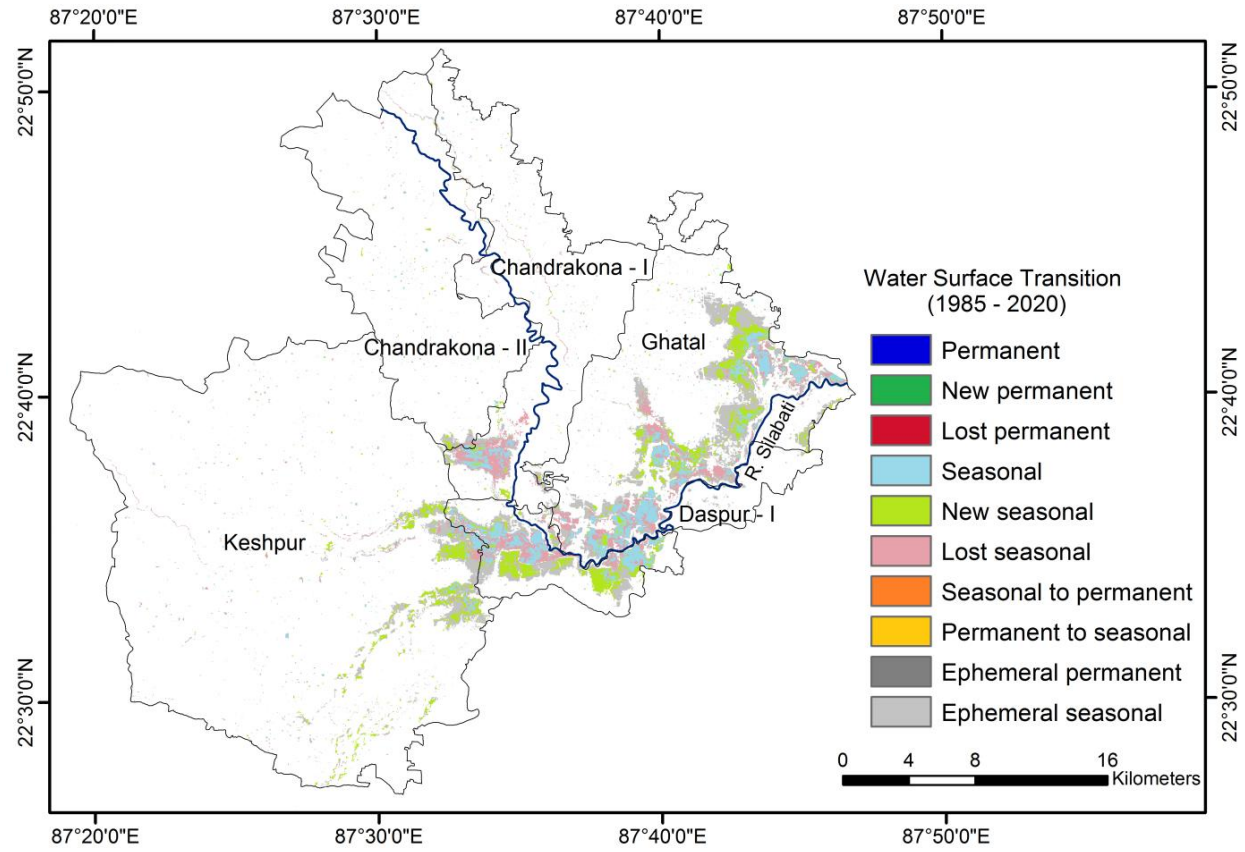


Fig. 21: Map showing seasonal water surface transition from one landuse class to another

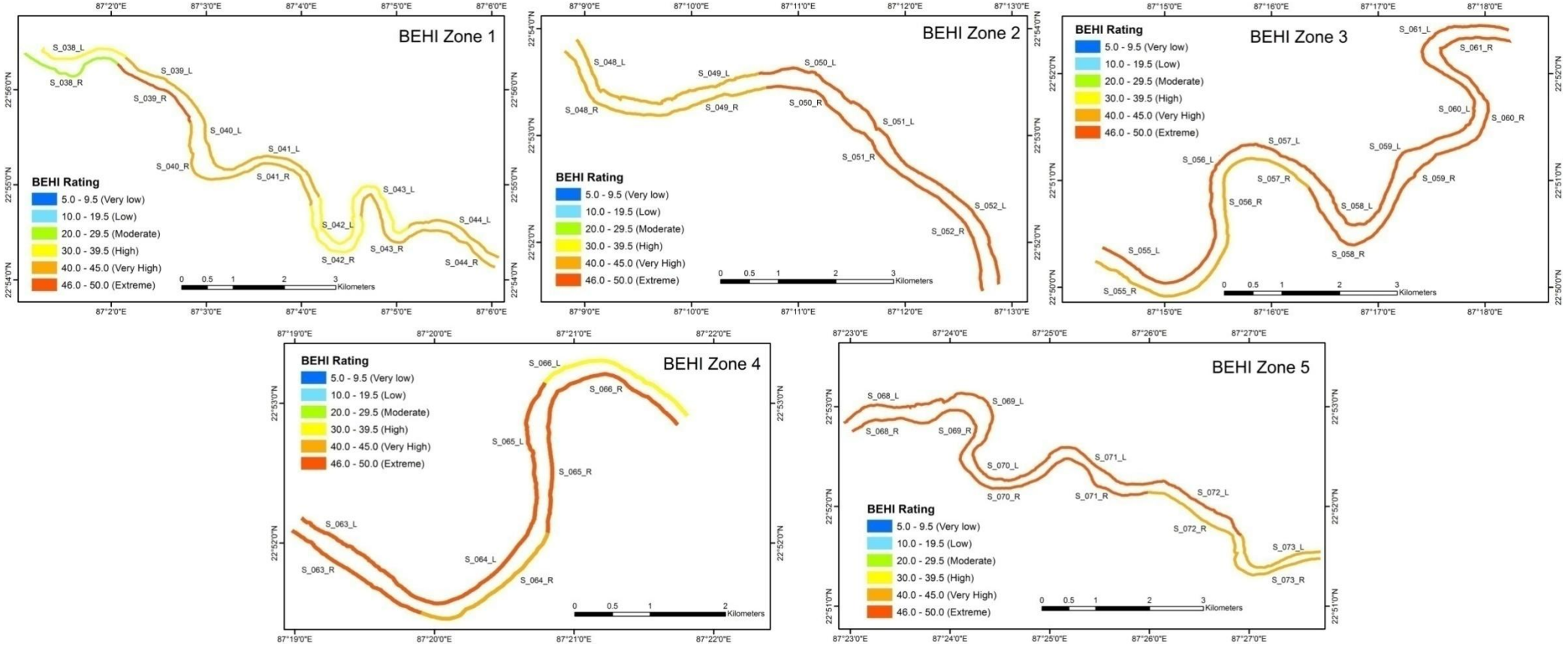


Fig. 22a: Map showing erodibility status of vulnerable banks calculated according to Bank Erosion Hazard Index (BEHI) along the middle course

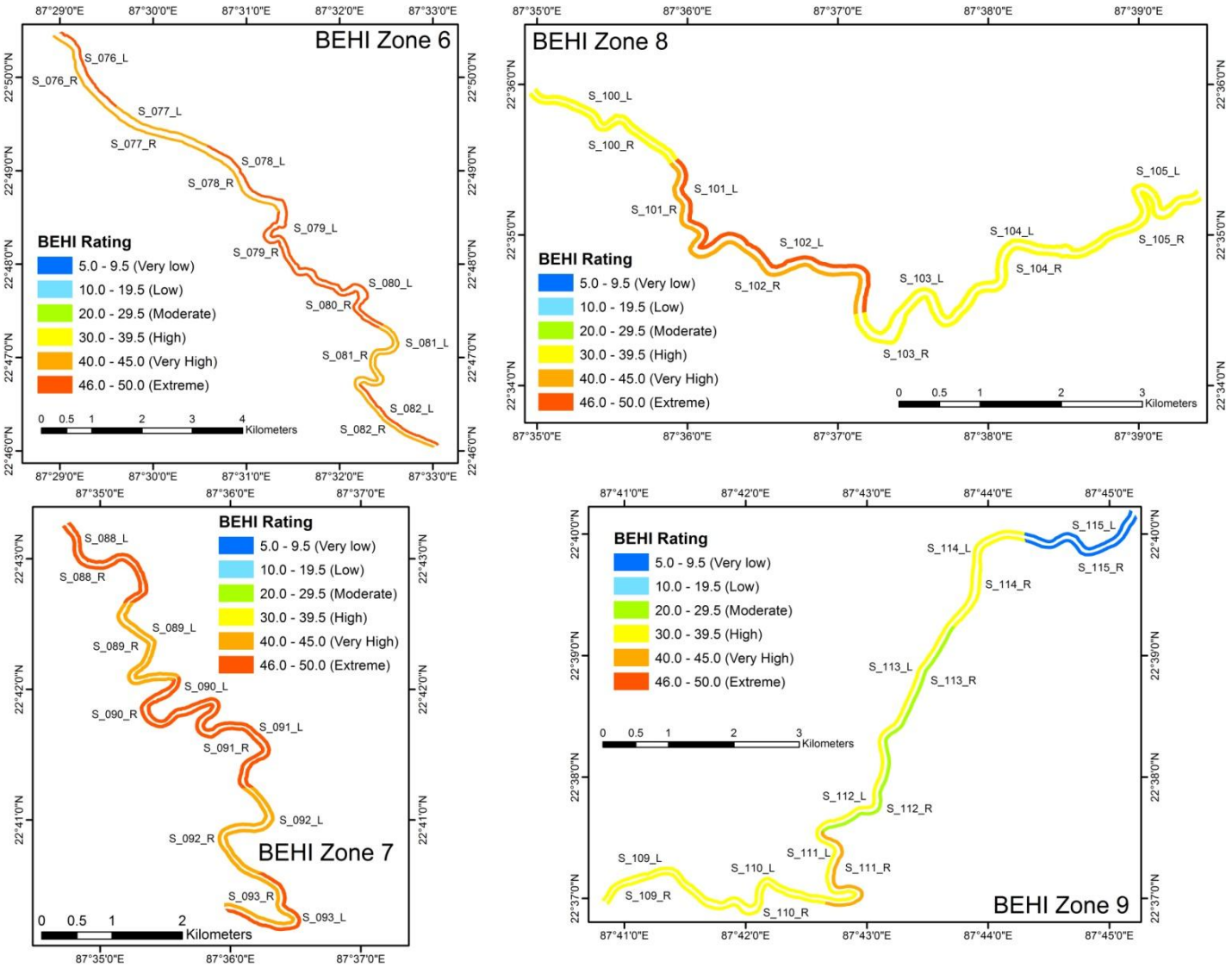


Fig. 22b: Map showing erodibility of vulnerable banks calculated according to BEHI along the lower course

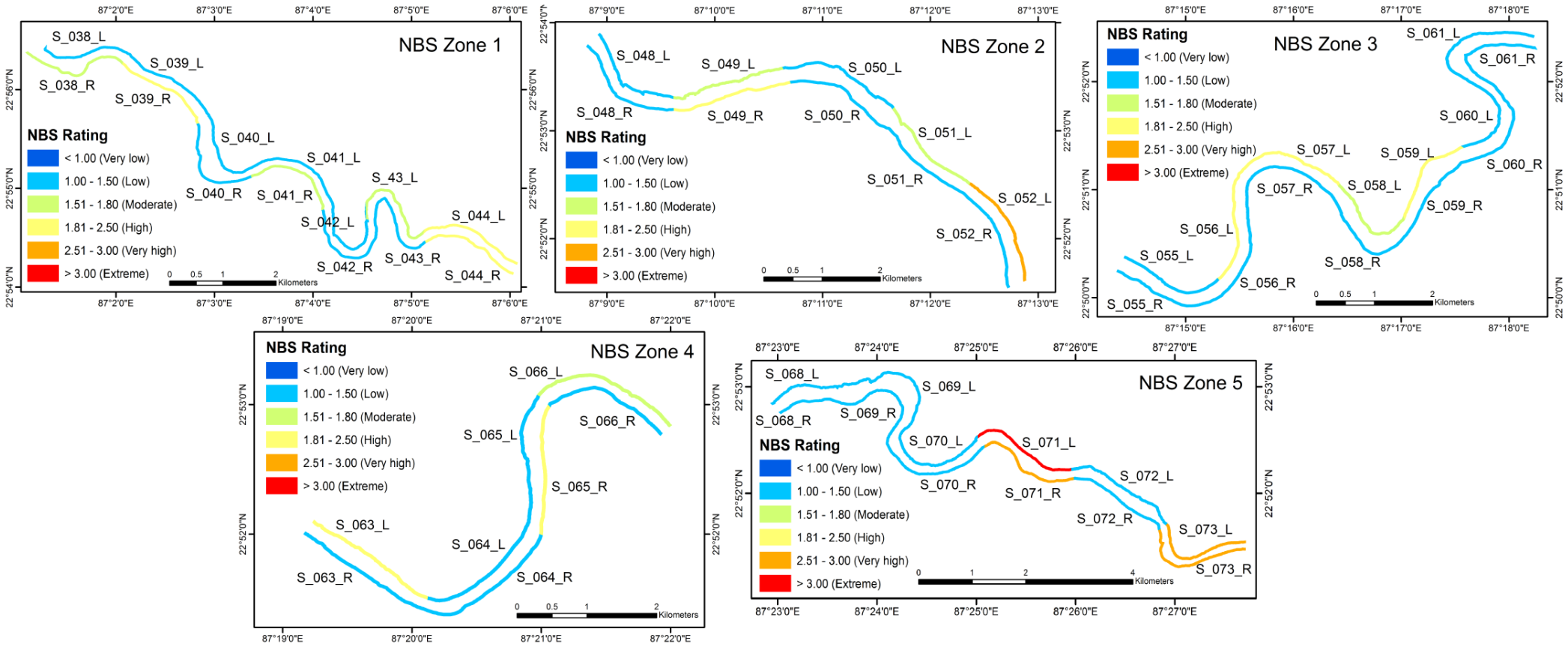


Fig. 23a: Near-bank stress (NBS) distribution along the middle course of the channel

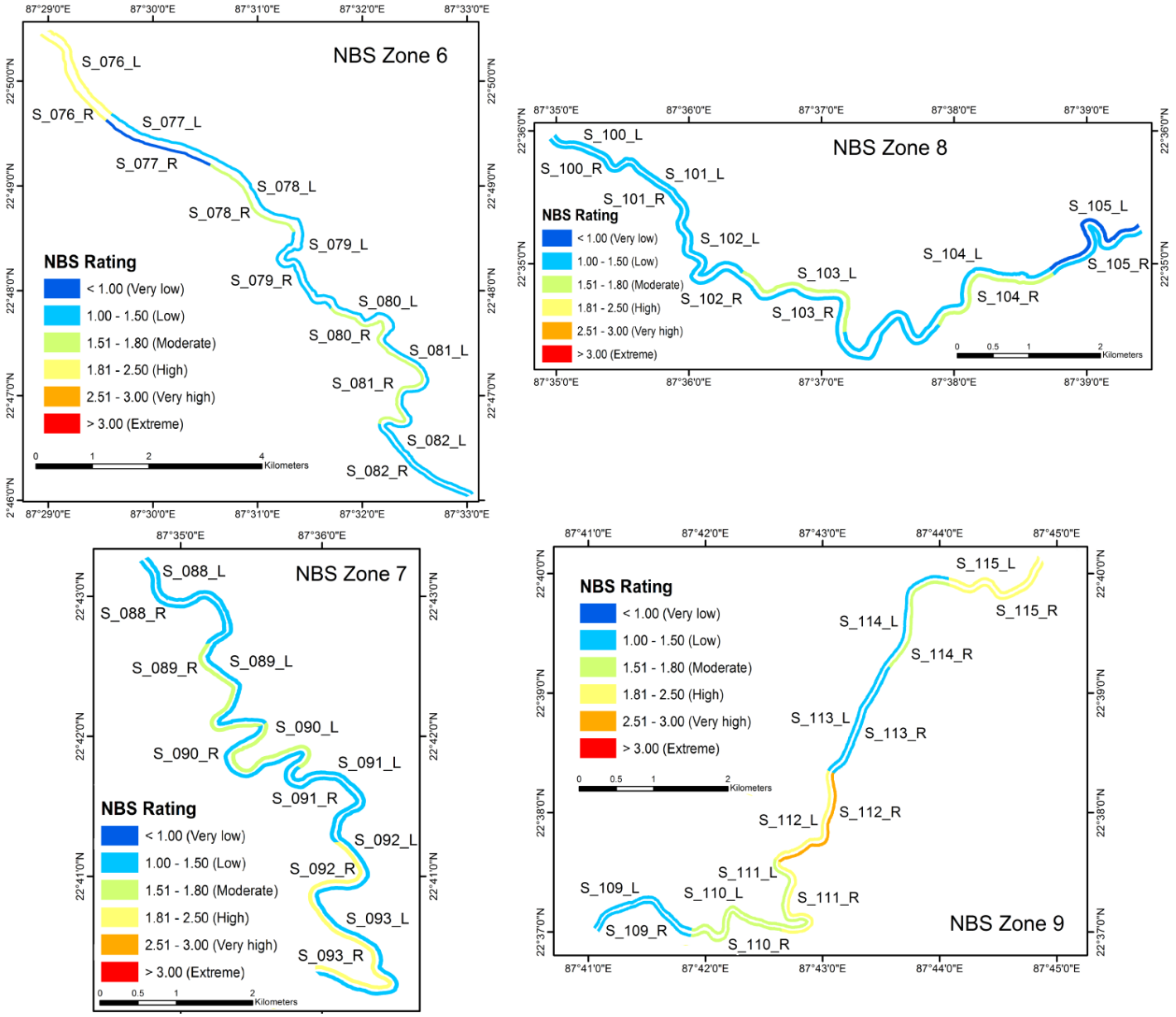


Fig. 23b: Near-bank Stress (NBS) distribution along the lower course of the channel

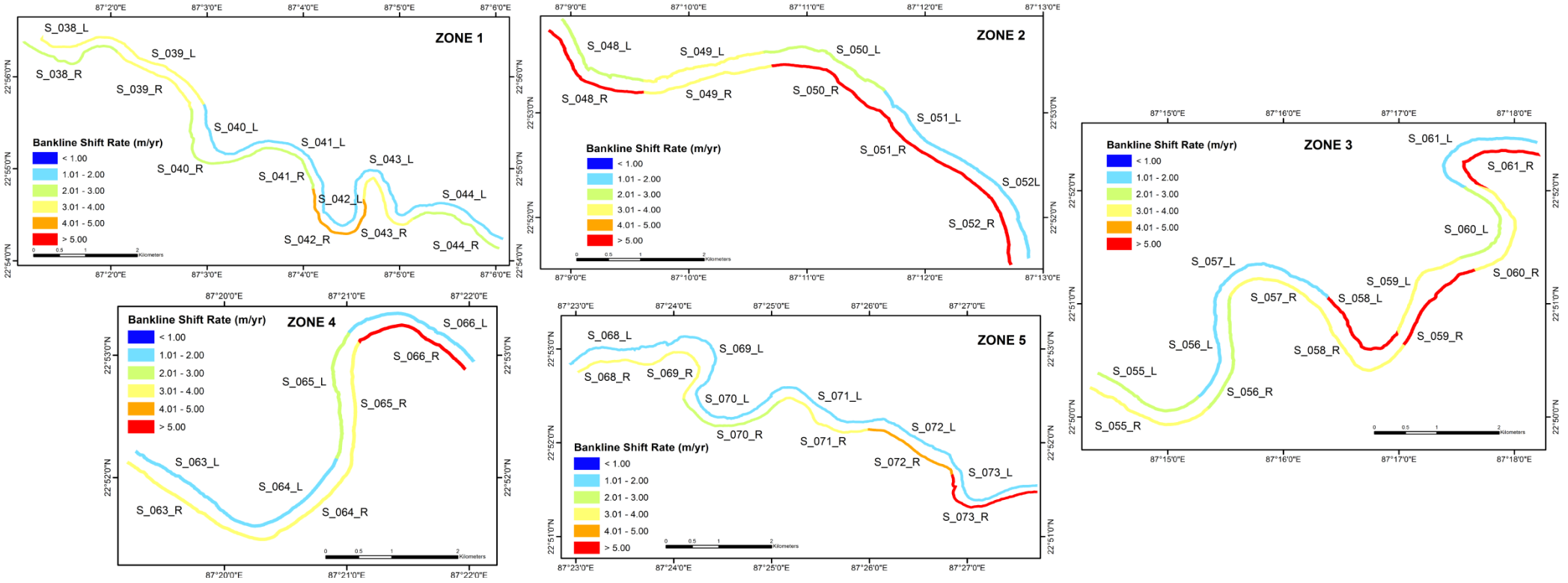


Fig. 24a: Predicted bankline shift rates for both banks along the middle course of the channel

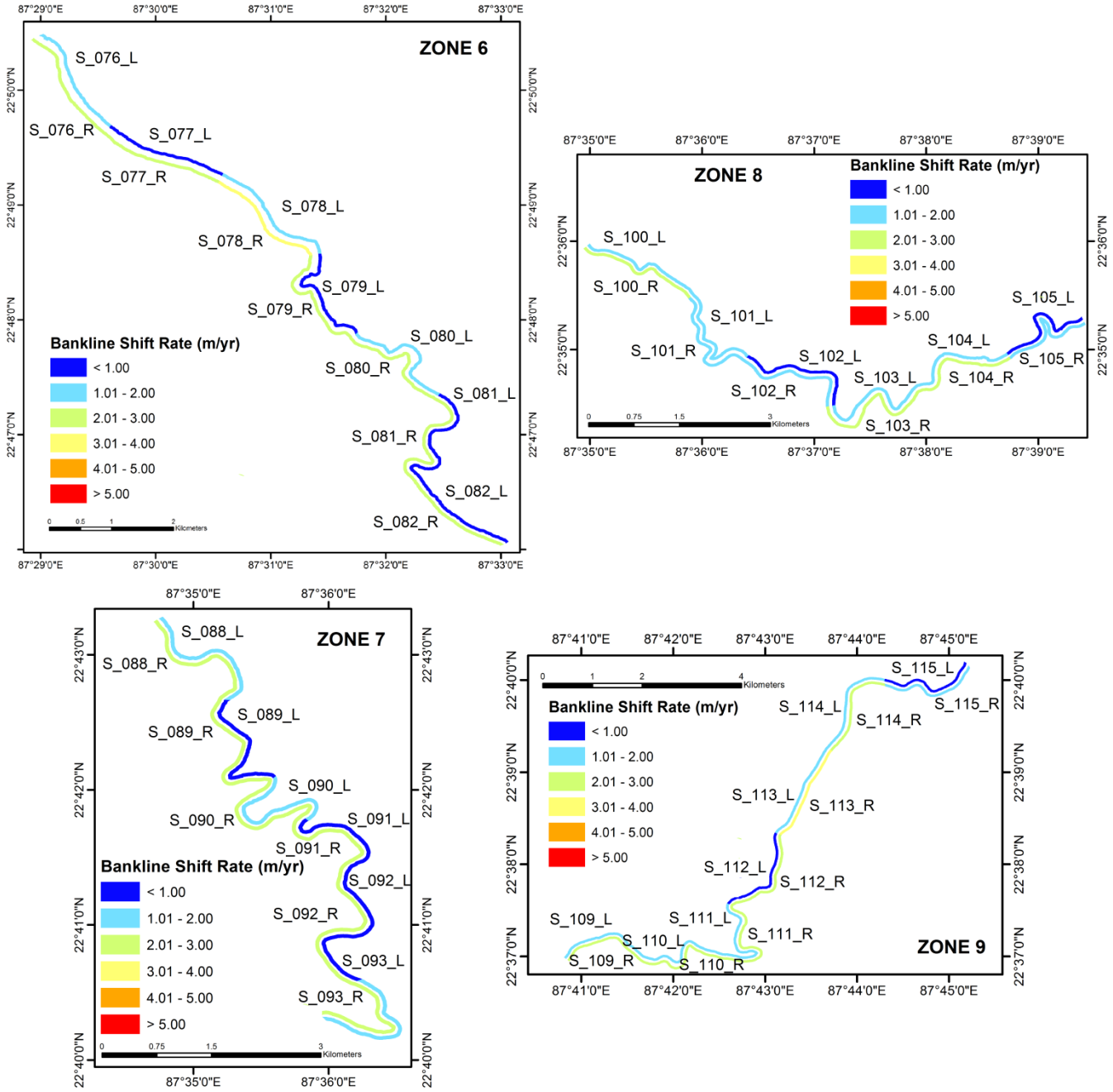


Fig. 24b: Predicted bankline shift rates for both banks along the lower course of the channel

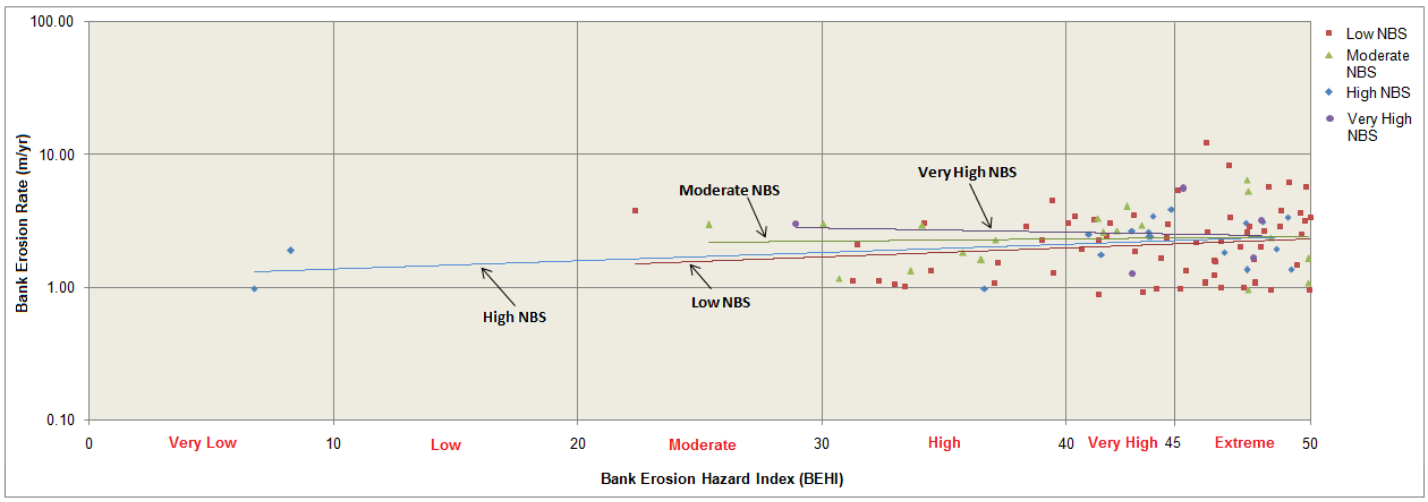
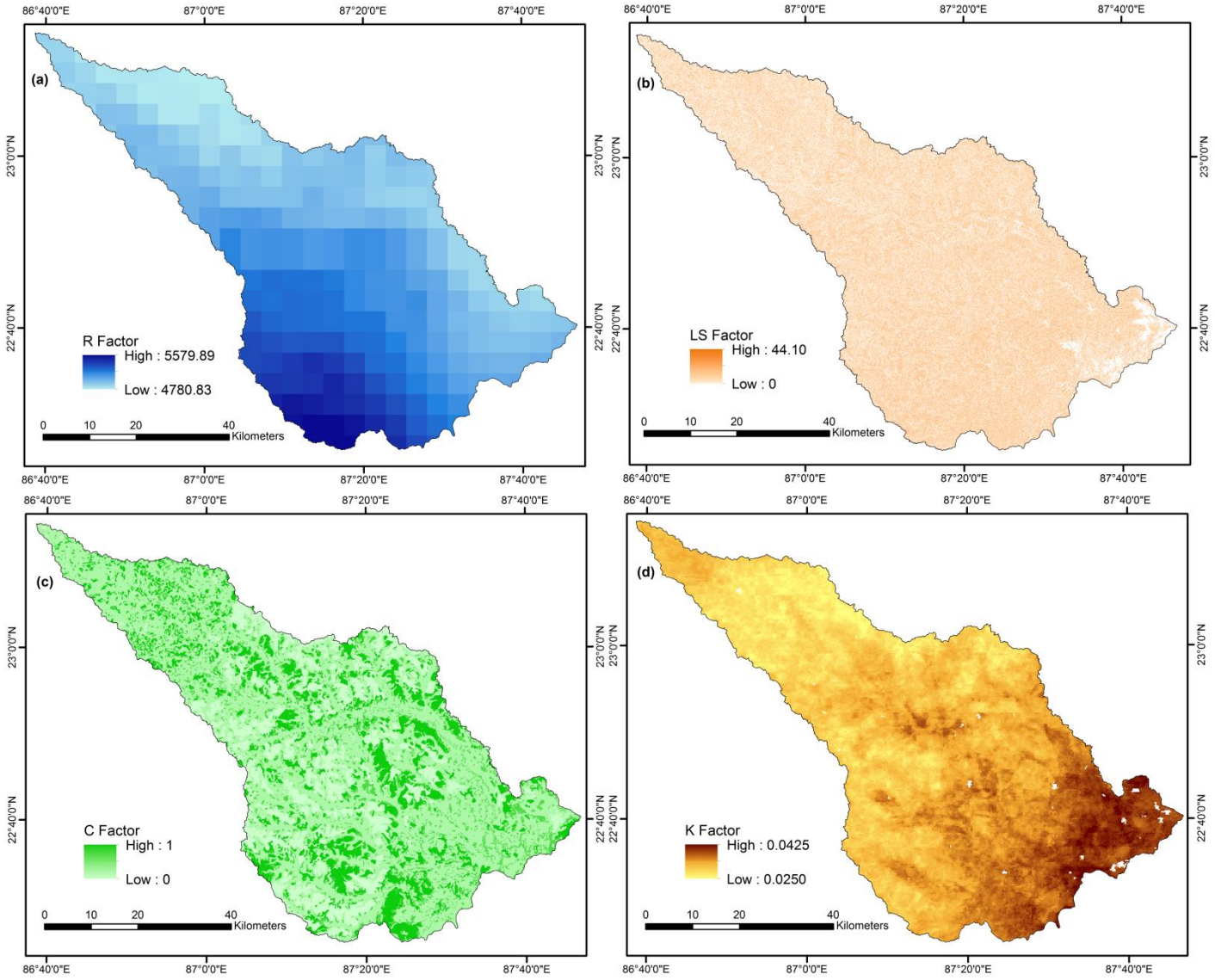


Fig. 25: Plots of BEHI and actual bankline shift rates according to NBS rating



26: USLE Factor Maps- (a) R factor - rainfall erosivity, (b) LS factor - slope length and steepness, (c) C factor - conservation/management practices, and (d) K factor - soil erodibility

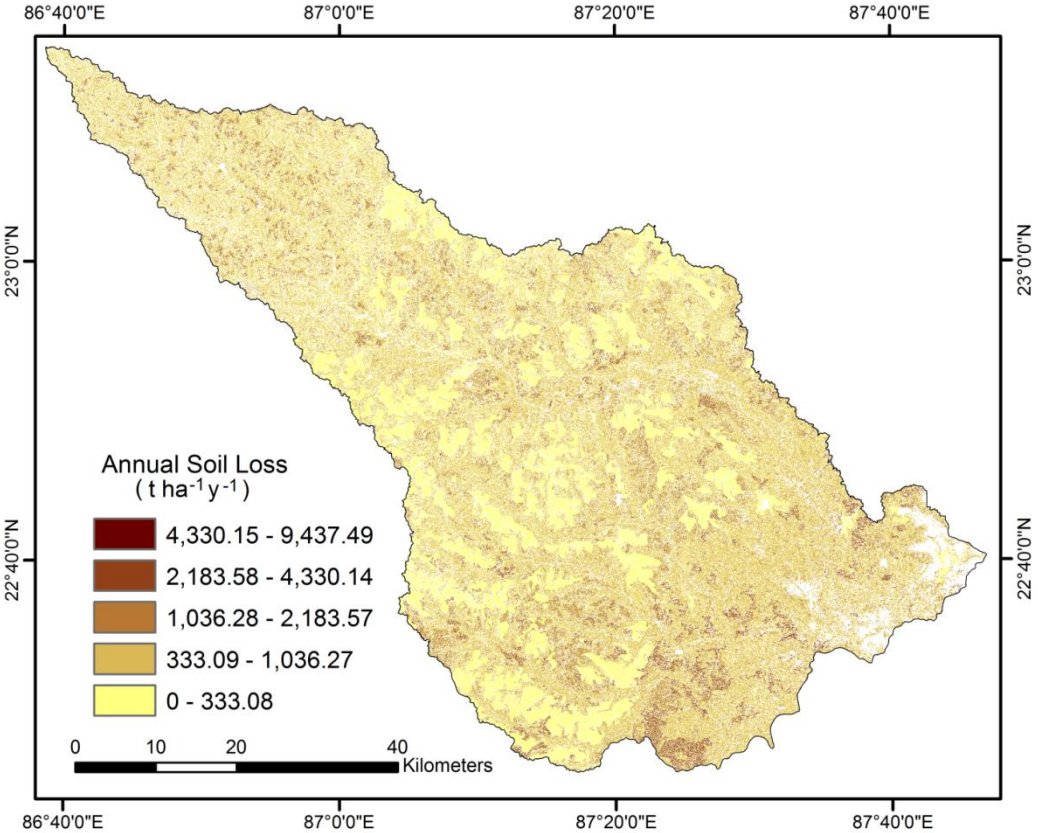


Fig. 27: Mean Annual Soil Loss from the Silai Basin

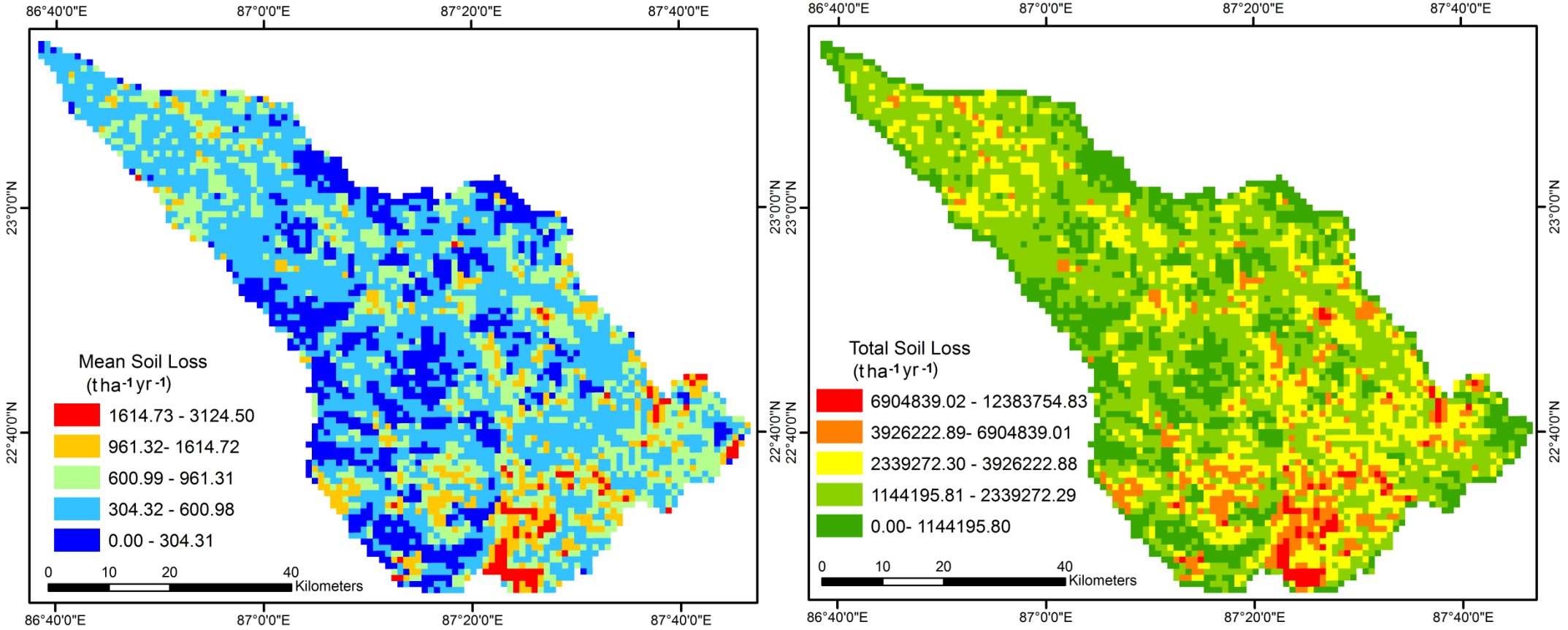


Fig. 28: Mean and Total Annual Soil Loss computed for each 1 km × 1 km grid overlain across the Silai River Basin

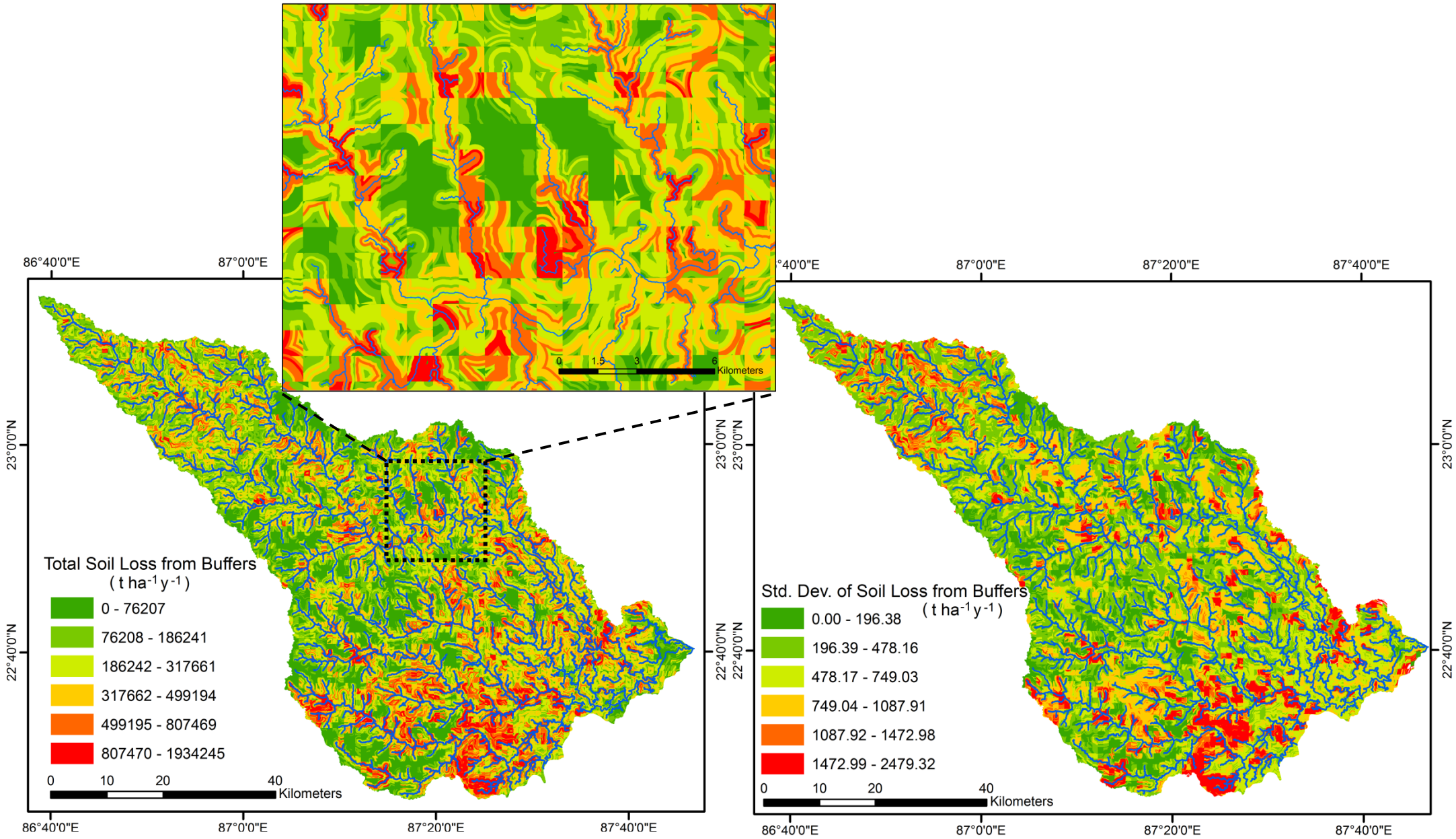


Fig. 29: Total annual soil loss from consecutive 50 m wide and ~1 km long buffer strips along the Silai River and its tributaries, with inset

This chapter focuses on the use of ecological techniques, mainly live vegetative buffers, along the river corridor to reduce flood velocities and promote riverbank slope stability, thereby mitigating these hazards' effects. Among other native bioengineering grasses, Vetiver grass (*Vetiveria zizanioides*) has been suggested as one of the most promising solutions to stabilise eroding banks in terms of its cost-effectiveness and long-term resilience (Maffei, 2002; Okon & Babalola, 2004) (Fig. 30). Being native to the tropical belt, this perennial, tall, non-invasive, densely tufted grass can tolerate temperatures ranging from -14 °C to 55 °C and survive stretches of drought and heavy rainfall (National Research Council, 1993; Truong, 1999). It grows luxuriantly in regions receiving annual rainfall between 100 - 200 cm (Dudai et al., 2006) and can colonise most topographic forms, from hill slopes to lowland plains and riverbanks (Maffei, 2002). Dense Vetiver grass hedges provide a two-way support to eroding slopes– the deep, interlocking fibrous roots penetrate down to 3.0 - 4.5 m beneath the surface and bind soil particles while the aboveground growth extends up to a height of 1.2 m, trapping sediments and reducing the runoff velocity (Zeitz, 2015; Yinglun, 2018). It acts as an excellent phytoremediator and has been highly acclaimed for its use in soil-water conservation, slope stabilisation, essential oil extraction and in creating handicrafts (Tripathy et al., 2014; Gnansounou et al., 2017).

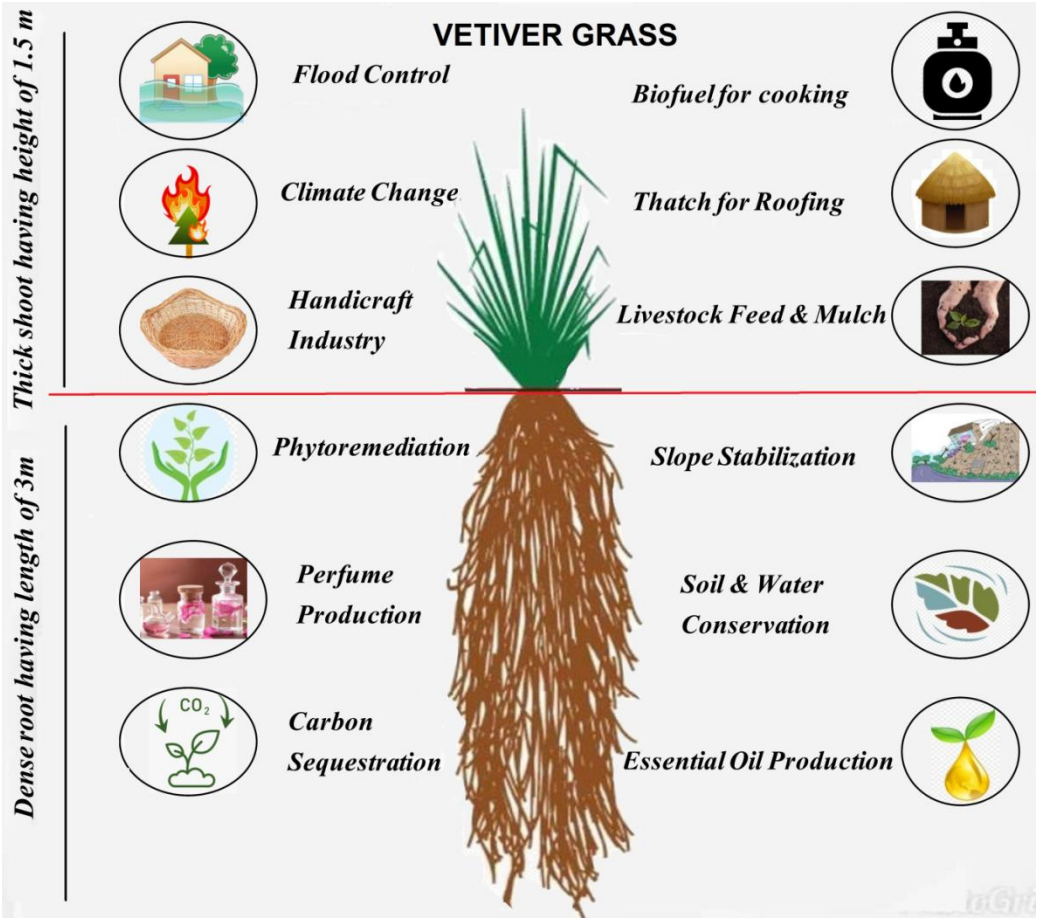


Fig. 30: General characteristics of Vetiver grass depicting its multipurpose benefits

The impacts of the grass' root network on the soil physicochemical properties and how this enables riverbank protection and lessen flood impacts have been examined. A schematic diagram of the chronology of workflow is presented (Fig. 31). Undisturbed soil samples were collected at two different depths of 0-10 cm and 10-20 cm below the surface along the banks of River Ketia (beside Kuthighat and Gholsai villages) where Vetiver grass has been planted. Soil physico-chemical properties like saturated hydraulic conductivity (K_{sat}), dry bulk density (BD), soil organic matter (SOM), soil aggregate stability and mean weight diameter were evaluated in the respective treatment and control plots.

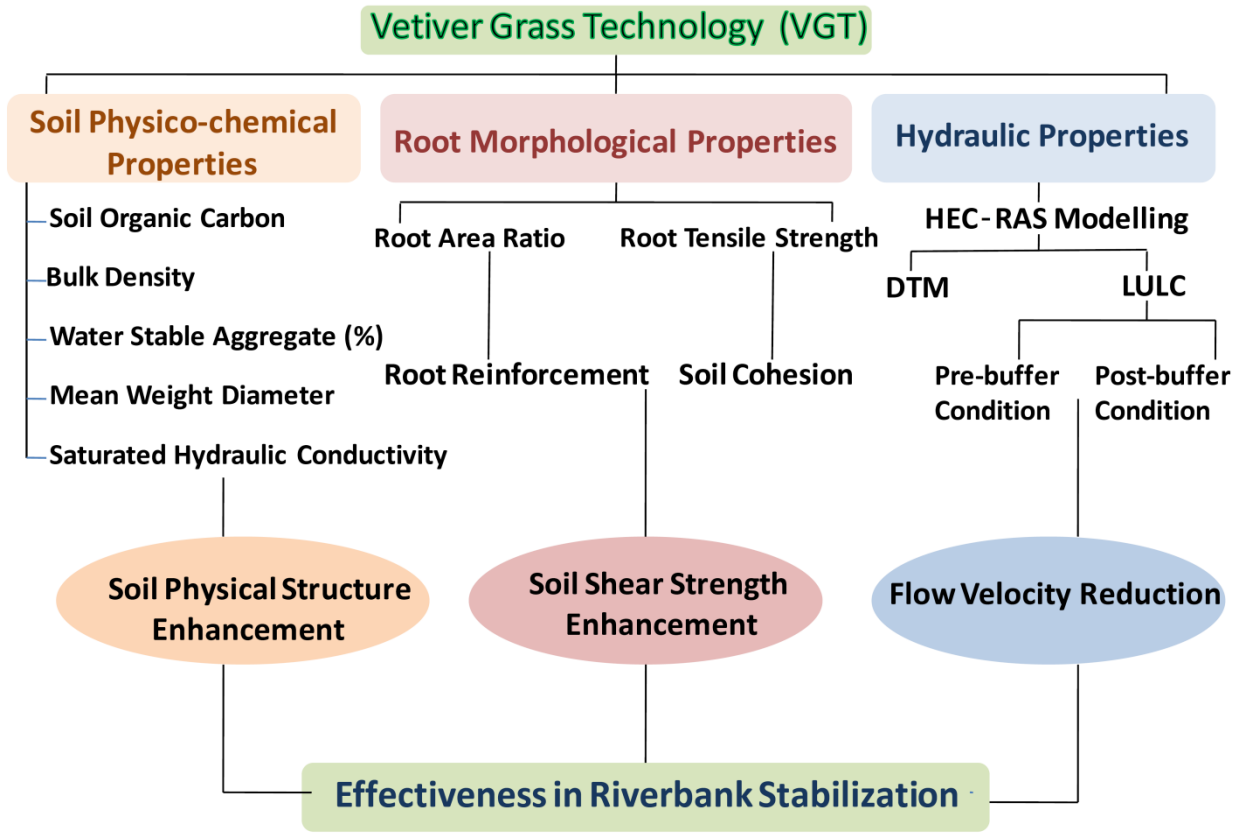


Fig. 31: Schematic diagram depicting methodology followed in the study

The mechanical root reinforcement property of the grass was examined using root morphological indices like root area ratio and root tensile strength. ImageJ software (Schneider et al., 2012) was used to measure individual root lengths of the grass. Root Area Ratio (RAR) values have been cited from the existing literature and root tensile strength was measured using a Universal Testing Machine (UTS). The increase in soil cohesion and shear strength due to root reinforcement into the soil was calculated using the traditional Mohr- Coulomb failure Criterion wherein the internal friction angle and added cohesion due to Vetiver roots were measured by the triaxial compression test conducted on undisturbed soil cores collected from both the sites.

The collected soil samples were all of brownish grey clayey silt, as ascertained from their respective textural classification. K_{sat} values show marked variation between treatment (i.e. VGT implemented) and control (bare) plots and also across different soil depths (Fig. 32a). At Kuthighat, these values revealed a 57.9% increase in treatment plots (0.06 cm/hr) compared to the control plots (0.038 cm/hr) at a soil depth of 0-10 cm, while for the 10-20 cm soil depth the corresponding values were 0.018 cm/hr and 0.019 cm.hr, respectively, decreasing by 5.3%. At Gholsai too, treatment plot values (0.28 cm/hr) revealed an increase in the hydraulic conductivity by almost 154.5% for the surface soil layer (0-10 cm) as compared to values from control plots (0.11 cm/hr) that were either bare or had short, sparse local grass cover. Contrastingly, the corresponding values for the sub-surface layer (10-20 cm) showed a 70.8% rise (0.82 cm/hr in the treatment plot and 0.48 cm/hr in the control plot). The SOM had also increased considerably in the samples taken along VGT banks as compared to those from the control bank at both sites (Fig.32b). The organic carbon content at Kuthighat had risen from 0.31% to 1.16% and at Gholsai from 0.71% to 1.45% from the control to the treatment plots, respectively.

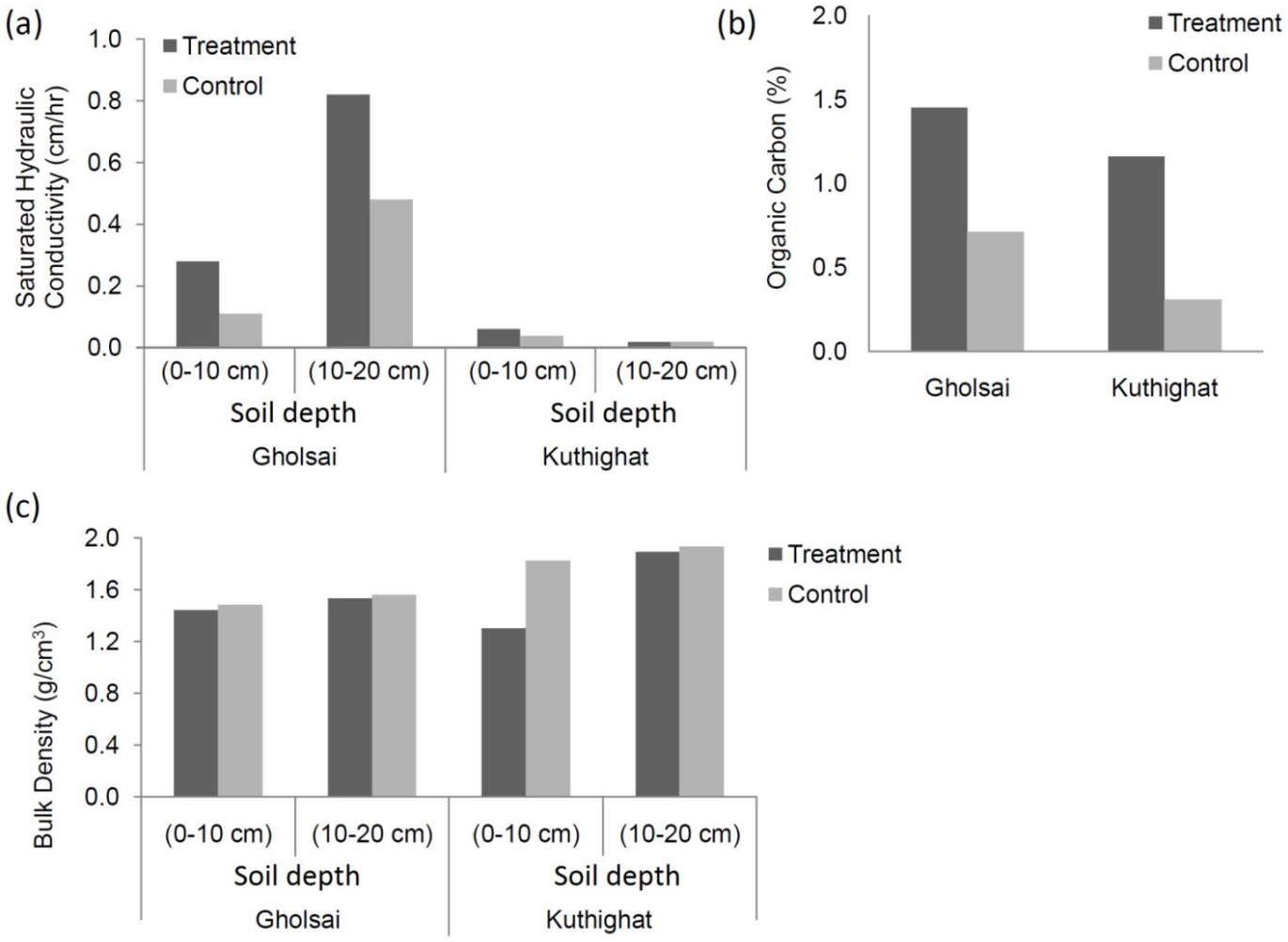


Fig. 32: Measured physico-chemical parameters for the soil samples- (a) saturated hydraulic conductivity, (b) soil organic matter and (c) dry bulk density

The dry bulk density (BD) gradually decreases with increasing vegetal cover and root penetration, while it increases with soil depth within the same soil profile. Both the sampled sites record the above trend (Fig. 32c). In treatment plot samples at Gholsai, BD values (1.44 g/cm^3) had decreased by 2.7% compared to samples from the control plot (1.48 g/cm^3) for the surface soil layer. For the same soil depth at Kuthighat, BD values decreased by 28.6% (1.56 g/cm^3 to 1.53 g/cm^3) from control to treatment plots. BD values increased at greater soil depth (10-20 cm) in both control and treatment plots at the two villages compared to the values in the surface soil layer (0-10 cm). This increase was most in the treatment plot at Kuthighat (from 1.30 g/cm^3 to 1.89 g/cm^3).

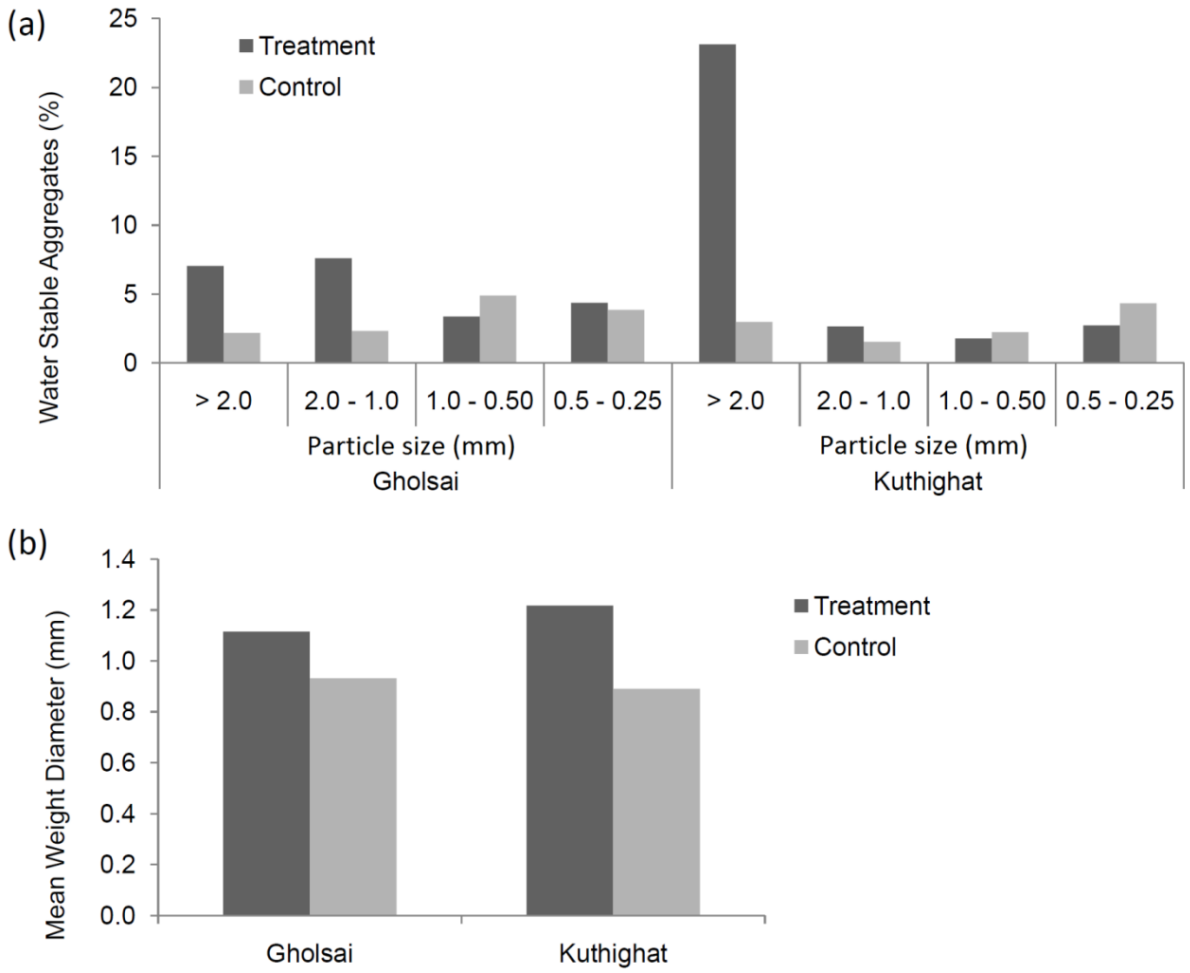


Fig. 33: Extracted values for - (a) water stable aggregates of varying particle sizes and (b) mean weight diameter

The aggregate stability of the larger soil particles increased at both sites within their VGT plots (Fig. 33a). At Kuthighat, all the water-stable aggregate size classes (WSA > 0.25 mm) together comprised 30.3% in the treatment plots, increasing from a total of 11.1% in the control plots, while in Gholsai, the corresponding values were 22.4% and 13.2%, respectively. MWD

values had also increased in the treatment plots compared to the control samples (Fig. 33b), with Kuthighat experiencing a positive change of 36.7% (from 0.89 mm to 1.22 mm) and Gholsai, 19.5% (from 0.93 mm to 1.11 mm). While macro aggregates having mean diameter 1.5 - 2.0 mm and covering the surface soil increased as a result of VGT (the grass induces more organic matter in the upper soil layer, promoting soil cohesion and formation of larger particles that are harder to erode, thereby making the bank more resistant), smaller aggregates tend to naturally disintegrate far more easily and thus showed a proportional decline. Thus the Vetiver grass' root penetration into the sub-soil and concomitant increase in the aboveground vegetal cover modified the soil physicochemical properties, improving its structure and ability to prevent detachment.

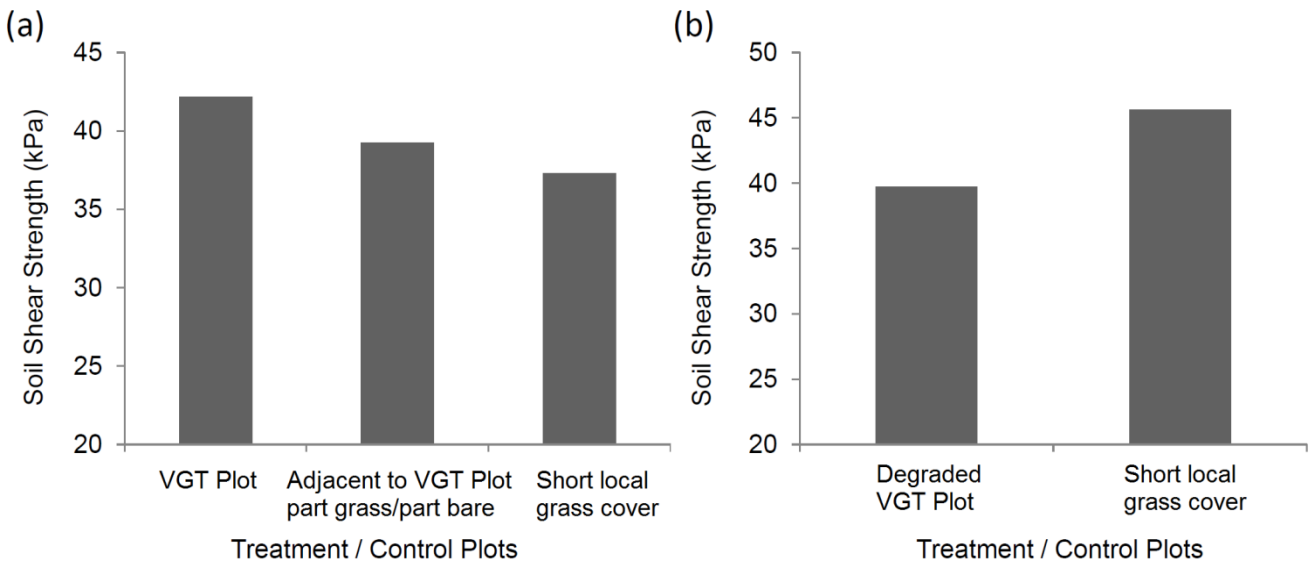


Fig. 34: Measured soil cohesion values for collected soil samples from different sites- (a) at Gholsai and (b) at Kuthighat

The enumerated shear strength parameter of cohesion (*c*) indicated a rise in the soil shear strength as a result of root reinforcement at both sites. In Gholsai (Fig. 34a), samples from the present VGT plot had the highest shear strength value of 42.17 kPa, followed by those from the plot adjacent to it (shear strength value 39.23 kPa). The local grass covered plot's samples had the lowest shear strength value (37.27 kPa). Therefore, the cohesion and shear strength in the VGT plot had increased by almost 13.15%, compared to original local conditions (i.e. ground covered by short local grasses), while the presence of the Vetiver grass seemingly had had some binding effect on the soil profile in the immediately adjacent tracts. However, in Kuthighat a different scenario came to light (Fig. 34b). The local grass covered plot had a higher cohesion value of 45.61 kPa, while samples taken from parts of the former densely planted Vetiver plot that has now become quite degraded due to grazing and ill maintenance, elicited a lower shear strength value of 39.72 kPa. This shows the utmost need for maintenance of the Vetiver buffer.

The probable effect of the aboveground VGT biomass in reducing flow velocities during flood events was modelled in HEC-RAS by first simulating (1-D method) an actual flood event and then a scenario where Vetiver grass buffers line the channel and adjacent floodplain. A 5 m spatial resolution Digital Terrain Model (DTM) (Takau et al., 2014; 2016) for the lower stretch of the River Silabati from Gadighat to Pratappur (Fig. 35), was used for this purpose. Water-level data obtained from the Gadighat gauge station on the River Silai for the 2017 monsoon period (June to October), was used. The highest flood peak had occurred on 26 July 2017, with a recorded gauge level of 9.90 m at Gadighat (0.3 m above the mandated extreme danger level), as documented by the Irrigation & Waterways Department, Government of West Bengal. Two different scenarios were modelled: Firstly the presently existing land cover and land use (LULC) condition was utilised in which the lands just adjacent to the channel are either cultivated tracts or are part of Ghatal town (Fig. 36a). This was termed as the 'Pre-Buffer Stage'. Secondly, a hypothetical LULC scenario was developed (Fig. 36b) wherein a 100 m wide Vetiver grass buffer strip was delineated (i.e. the 'Post-Buffer Stage') along both riverbanks and also along the immediately adjacent floodplain tracts (leaving aside those patches already occupied by settlements as these cannot be feasibly transformed into a bioengineered riparian buffer). The Manning's roughness coefficient values for the different existing LULC classes were obtained from the relevant literature (Table 4), while the values for the riverbank and floodplain Vetiver cover/hedge were collated from published values based on extensive flume experiments conducted by Doncker et al. (2009) and Dalton et al. (1996) on this particular grass (Table 4). To visually corroborate the derived flood inundation outputs, RapidEye image mosaics (spatial resolution– 5 m) for July and October of 2017 were used from the Planet.com archive.

Three section lines were drawn across the channel and the flow velocity values extracted along them plotted (Fig. 37). Along section 1, the velocity has reduced from 0.38 m/s to 0.32 m/s on its left bank margin from the pre-buffer stage to the post-buffer stage, while it has reduced from 0.39 m/s to 0.18 m/s on its right bank margin. The corresponding values derived for the section line 2 were 0.75 m/s to 0.7 m/s (left bank) and 0.89 m/s to 0.77 m/s (right bank), while for section line 3 these were 0.86 m/s to 0.83 m/s (left bank) and 0.65 m/s to 0.61 m/s (right bank). Even within the central portion of the channel, there is reduction in the higher flow velocities (from 0.6 m/s to 0.35 m/s along section line 1, from 1.5 m/s to 1.01 m/s along section line 2 and from 2.0 m/s to 1.21 m/s along section 3). Overall, the HEC-RAS derived results showed that an installed Vetiver grass buffer could effectively reduce the flood peak velocity by almost 0.8 - 1.0 m/s along most of the channel (Fig. 38). This could be effective in protecting the banks from further erosion.

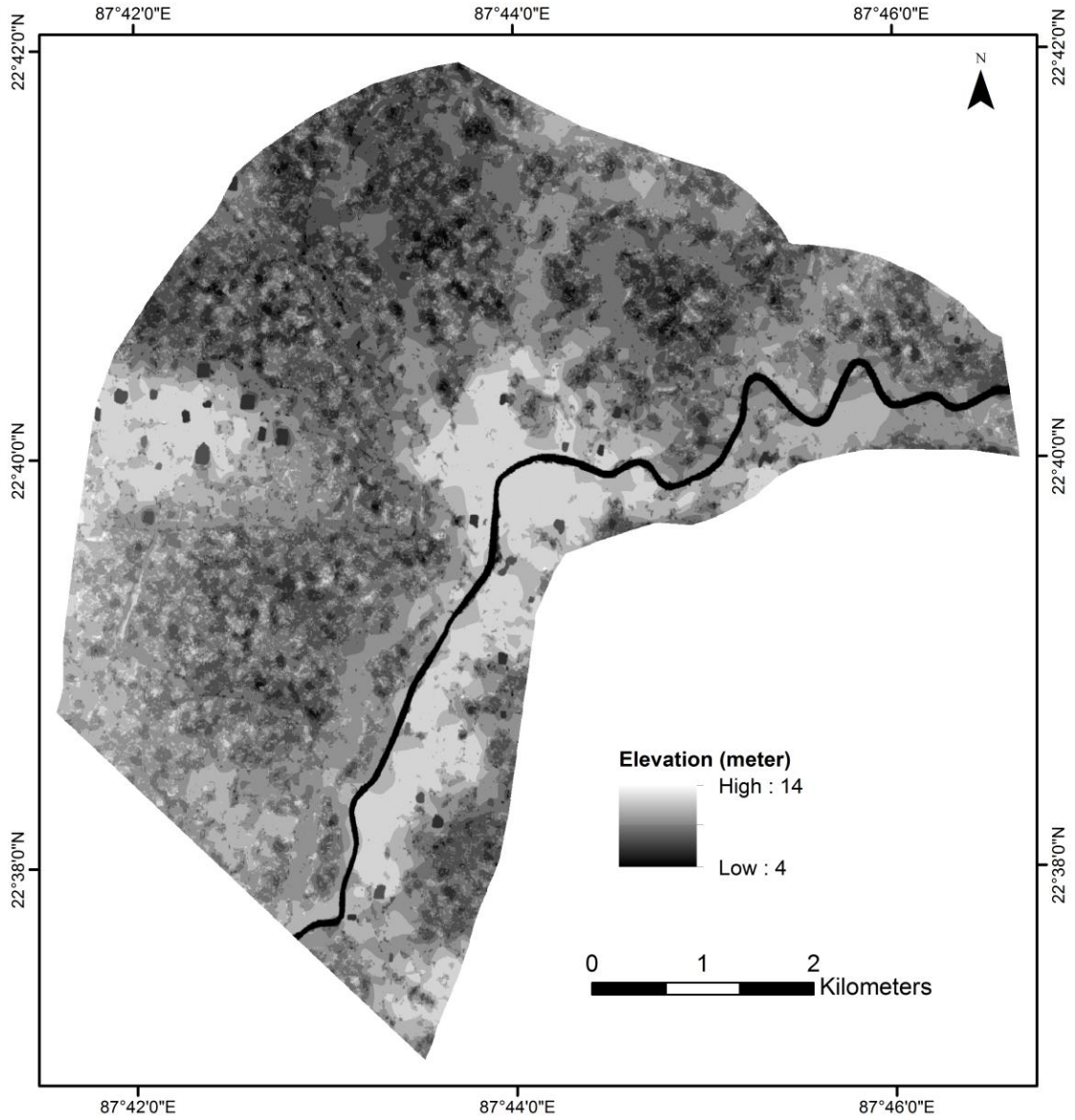


Fig. 35: Five meter resolution DTM (bare earth model) of the lower stretch of River Silai

Table 4: Manning's n values used for flood simulation exercises

LULC Class	Manning's n value	Reference
Natural vegetation	0.05	Chow, 1959
Cropland	0.04	Chow, 1959
River	0.045	Saksena et al., 2019
Ponds	0.001	Kalyanapu et al., 2009 based on USGS NLCD database
Built-up surface	0.0678	Kalyanapu et al., 2009 based on USGS NLCD database
Bare surface	0.0113	Kalyanapu et al., 2009 based on USGS NLCD database
Vetiver grass buffer along riverbank (on bank slopes)	0.09	Dalton et al., 1996; Doncker et al., 2009
Vetiver grass buffer along the floodplain (overbank portion)	0.16	Dalton et al., 1996; Doncker et al., 2009 and also considering values mentioned in Chow (1959) for dense grass covered floodplains (medium to dense brush in summer)

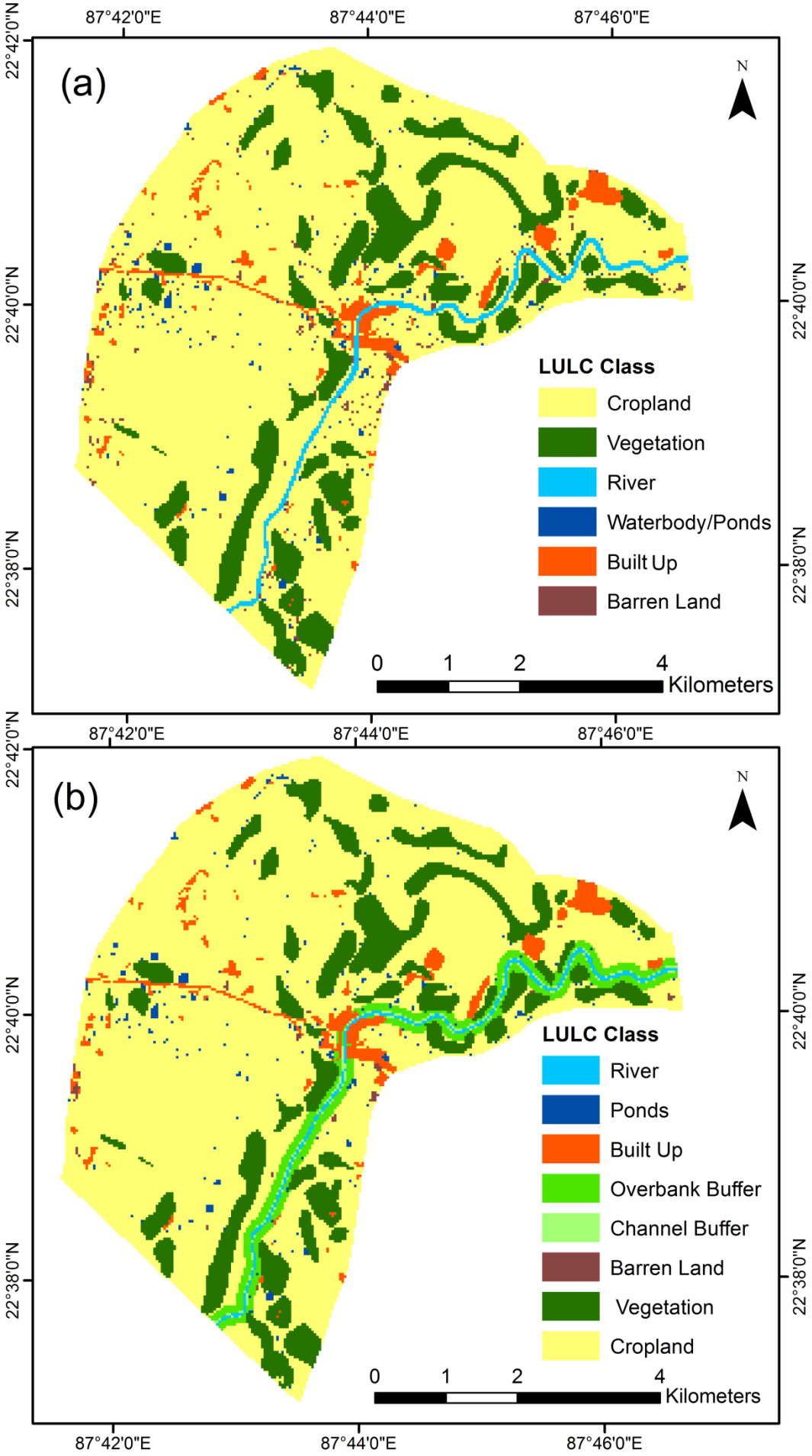


Fig. 36: LULC classes used in the modelling scenarios- (a) present LULC components along the river and (b) Delineated Vetiver grass buffer alongside both banks and floodplains

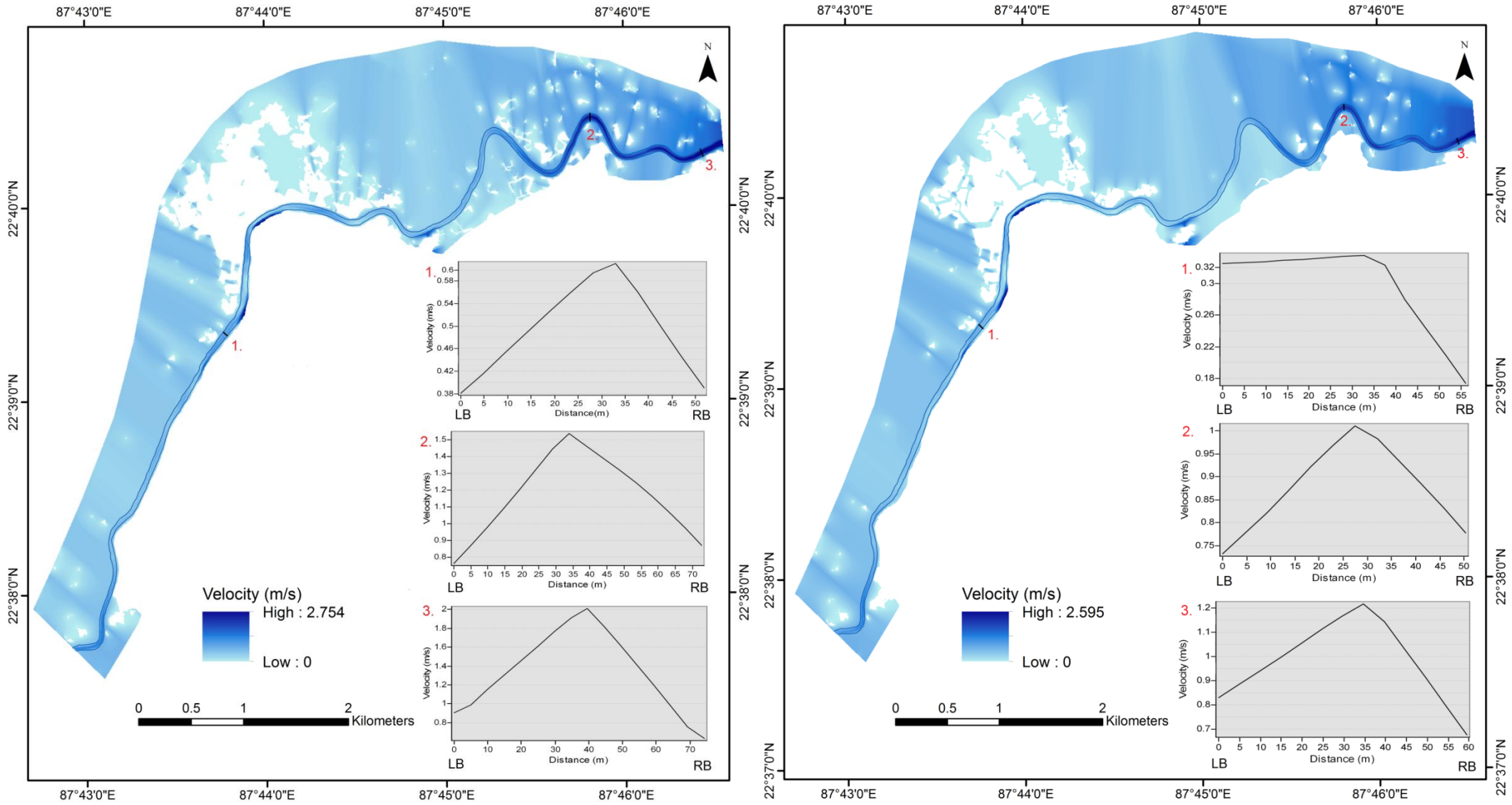


Fig. 37: (a) Modelled Pre-Buffer condition output for 26th July, 2017 with mapped flow velocities and (b) Modelled Post-Buffer condition output for 26th July, 2017 with mapped flow velocities

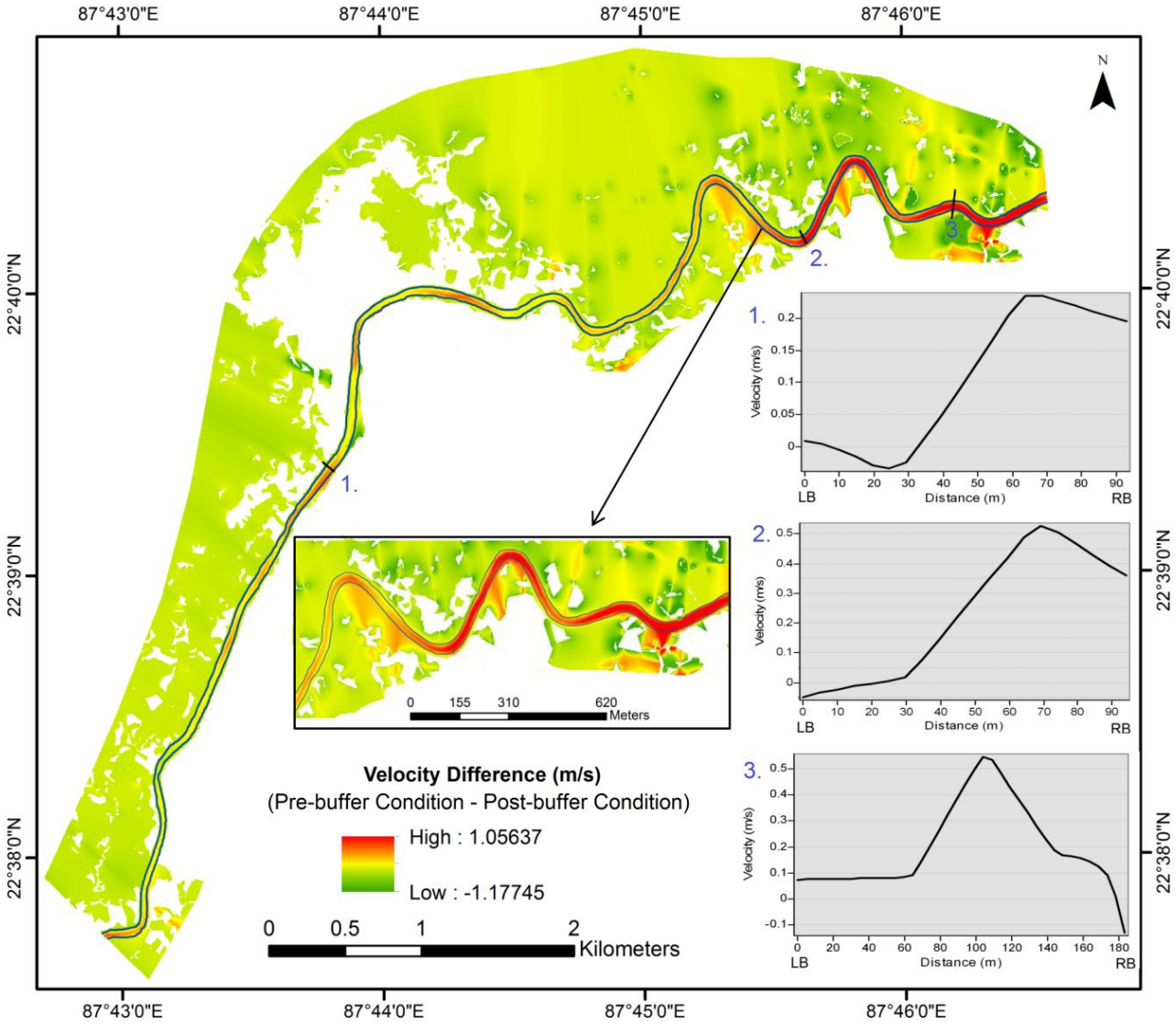


Fig. 38: Differences in river velocities between modelled Pre-Buffer and Post-Buffer scenarios for 26th July, 2017 flow simulations

A topographic survey using a Total Station was conducted at Gholsai village in January, 2019 and again in January, 2020, to gauge the erosion effect or otherwise of the intervening monsoon period on the respective channel flanks (Fig. 39) where comparison with the older cross-section has revealed that while the right bank had remained well-protected in the intervening monsoon, even though it was on the outer side of the meander bend, and had actually aggraded slightly by deposition of sediments along the bank footslope, the opposite left bank, which did not have a Vetiver grass buffer but was simply supported by bamboo stakes, had been eroded markedly and had suffered rotational slumping in several spots (Mondal & Patel, 2020).

The above discussion attests to the fact that Vetiver can be efficiently used not only as a slope stabilisation tool by positively changing soil physical structure and mechanical properties but also can reduce flow velocities during floods. Therefore it can feasibly be a most promising eco-engineering tool, especially in the tropical Global South, where floods and riverbank erosion

are common. Also, compared to hard-engineering measures, VGT installation incurs far less expense. It costs about Rs. 65 lakhs for re-constructing/repairing a 1 km breached earthen embankment using sandbags and riprap boulders while installing a ~600 m long Vetiver buffer cost about Rs. 799,191/- (Table 5 and Table 6).

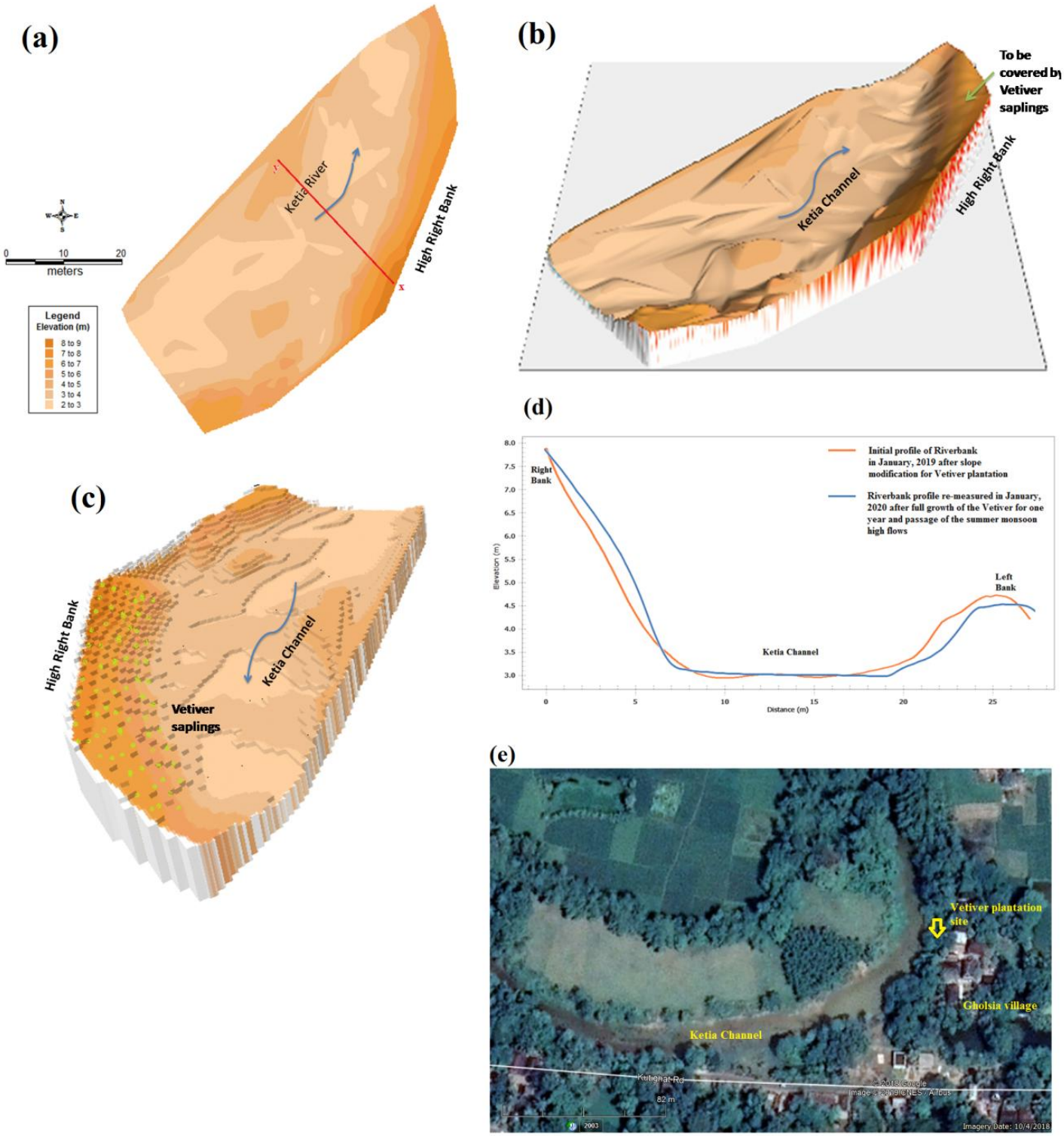


Fig. 39: Surface form of the modified riverbank at Gholsai site for planting the Vetiver- (a) bank elevation, (b) and (c) 3-D views, (d) channel cross-section taken at the site in January, 2019 and again in January, 2020 showing changes in channel dimensions, with the Vetiver-protected bank getting slightly aggraded and the eroding left bank and (e) Google Earth view of the site

Table 5: Cost of unskilled labour and wage components for the Vetiver plantation along the Ketia Channel at Gholsa i village

Sl. No.	Description of Items	Output of work/mandays	Total Quantity				Unskilled Labour (in person)	Rate (in INR)	Total Amount	
			Nos.	Length (m)	Breadth (m)	Quantity			INR	US $
1	Survey and Demarcation	75m/ Unskilled labour	1	594		594 m	7.92	191	1512.72	21.81
2	Initial cleaning/weeding of site	50.00sq.m/Unskilled labour	1	594	9	5346 sq.m.	106.92	191	20421.72	294.48
3	Labour for slope preparation and planting	5.00sq.m/Unskilled labour		594	9	5346 sq.m.	1069.2	191	204217.2	2944.84
4	Collecting local *Ipomea* (minimum length 4ft)	150 Unskilled labours				59.4 nos.	0.4	191	75.64	1.09
5	Planting *Ipomea* bars	50 Unskilled labours				59.4 nos.	1.19	191	226.91	3.27
6	Planting Vetiver saplings	150 saplings/Unskilled labour	120841			120841nos.	805.61	191	153871.51	2218.85
7	Labour required for fencing the site	10m/Unskilled labour				612 m	61.2	191	11689.2	168.56
8	Labour for first cleaning, mulching and cutting					594 m	11.88	191	2269.08	32.72
9	Labour for second cleaning, mulching/cutting					594 m	11.88	191	2269.08	32.72
10	Labour for third cleaning, mulching/cutting					594 m	11.88	191	2269.08	32.72
11	Labour for fourth cleaning, mulching/ cutting					594 m	11.88	191	2269.08	32.72
12	Watering and maintenance by self-help groups	1 Unskilled labour/500meters				120 nos.	142.56	191	27228.96	392.65
						Total Wage Component Cost =	**2243**		**428413**	6177.77

Table 6: Costs of material components for the Vetiver plantation along the Ketia Channel at Gholsia village

Sl. No.	Description of Items	Total Quantity	Rate (INR)	Total Amount	
				INR	US $
1	Cost of Plant	132925 nos.	2.5/ sapling	332312.5	4791.99
2	Cost of water pot for irrigation	6 nos.	200 each	1200	17.30
3	Fencing of site using bamboo nails and wires	612 m	15 meter	9180	132.38
4	Supervision of work (counting of wage labourers, taking attendance in master roll and other miscellaneous works	90 nos.	286.50/semi-skilled labour	25785	371.82
5	Display of permanent signboard	1 nos.	2300/board	2300	33.17
		Total Material Component Cost =		**370778**	5346.67

Source: Dewanchak-II Gram Panchayat Office, Ghatal Block, Paschim Medinipur District, West Bengal

Note: Amounts in INR have been converted to equivalent sums in USD on basis of the conversion rate on 15.04.2019

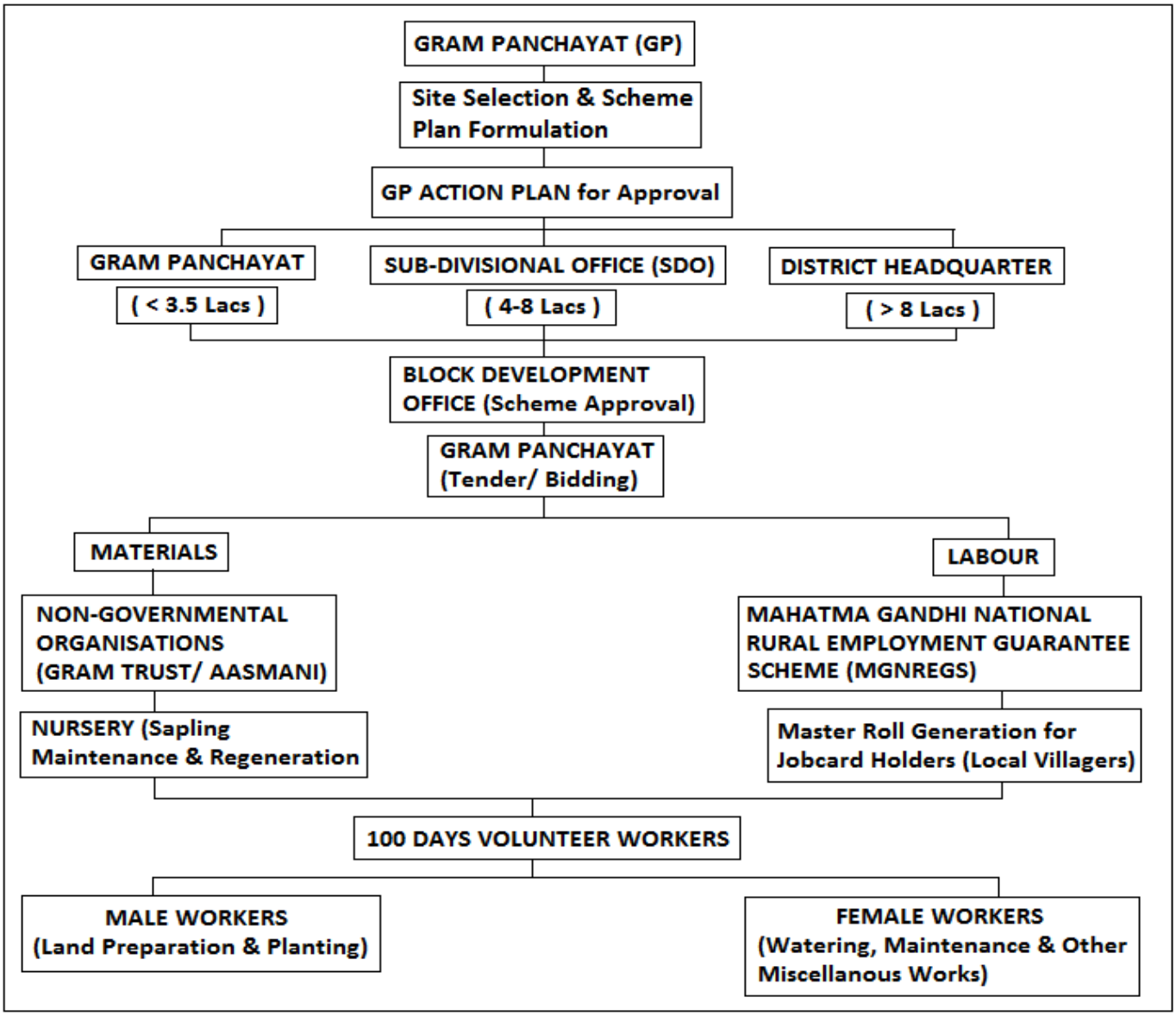


Fig. 40: VGT installation framework for riverbank protection as followed in West Bengal

Overview of slope stabilization costs to check soil erosion using geotextiles and VGT:

- Slope preparation cost - Rs. 158 per cub.m.
- Slope levelling and bioengineering materials jute geotextiles (500 GSM), Biomass component cocopeat and compost mix with planting of Vetiver clumps at 16 plants per sq.m - Rs.550 per sq.m
- Coir log [20 cm diameter x 1.0 m length each] to be fixed with bamboo pegs over slope as intermediate wall and toe wall and 10 m distance horizontal to the slope - Rs.440 per m
- Charges for comprehensive maintenance of site for all bio-engineering components for period of one year - Rs.160 per sq.m

Approximate Total Cost for slope treatment to conserve soil loss - Rs. 920 per sq.m

The framework used to implement the VGT in West Bengal by government agencies (Fig. 40) was explored and loopholes identified in the following points:

- Vetiver grass type to be used is most important (e.g. South India variety).
- Proper planting and grass growth time is essential (5-6 months growth must be ensured). So grass must be planted by November - December to provide protection for the next monsoon.
- Initial ground cover with geotextiles along with embankment or riverbank slope preparation.
- Proper fencing and care during and after growth – no cattle intrusion should be permitted.
- Few SHGs or cottage industries currently formed or developed for the VGT's by-products, which is a lacunae in local stakeholder involvement.

Conclusion

This thesis attempts to explore the overall health of the Silai River and its current geomorphic behaviour based on a number of multi-dimensional indices that tend to highlight the necessity of an integrated and interlinked approach to examine stream condition and then investigate sustainable, low-cost bioengineering methods that can be applied to mitigate to some degree the ambient stream health deterioration and impact of occurring fluvial hazards. A detailed reach-level analysis helped to delve into the various site-specific parameters for identifying the individual factors that impair stream health in each stretch. Assessment of the nature of the various fluvial hazards enabled devising the most suitable corridor management strategy that may minimise their negative impact on the stream. Vegetation-based ecological techniques using native grass species (Vetiver Grass) have been identified as the most suitable bioengineering measure herein that not only stabilises unstable slopes by providing root reinforcement but also reduces flood velocities that otherwise cause erosion. A cost comparison of this technique with the usual hard engineering methods usually implemented in the region showed this grass to be not only highly environment-friendly, but also cost-effective. The detailed analysis in this thesis could satisfactorily provide a viable ecological solution for stream restoration along the Lower Silai Corridor in the affected stretches and also a framework that can be applied in regions that face similar hazards.

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